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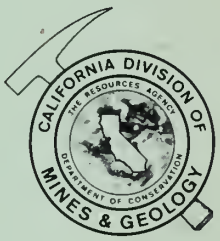
A REVIEW OF THE GEOLOGY AND EARTHQUAKE HISTORY OF THE NEWPORT-INGLEWOOD STRUCTURAL ZONE, SOUTHERN CALIFORNIA

1974

CALIFORNIA DIVISION OF MINES AND GEOLOGY

PREPARED IN COOPERATION WITH THE COUNTY OF LOS ANGELES, DEPARTMENT OF COUNTY ENGINEER AND THE LOS ANGELES COUNTY FLOOD CONTROL DISTRICT

SPECIAL REPORT 114



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Special Report 114

A REVIEW OF THE GEOLOGY AND EARTHQUAKE HISTORY OF THE NEWPORT-INGLEWOOD STRUCTURAL ZONE, SOUTHERN CALIFORNIA

This report is based on work completed in 1972.

By

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1974

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Prepared in cooperation with the
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ABSTRACT

The Newport-Inglewood structural zone trends northwesterly from Newport Mesa to the Cheviot Hills along the western side of the Los Angeles basin. This belt of domal hills and mesas, formed by the folding and faulting of a thick sequence of sedimentary rocks, is the surface expression of a major zone of deformation.

Near-surface faults associated with the uplifts act as barriers to the flow of ground water across the zone. The level of the water table east of the zone is thereby raised. In addition, the barriers help to prevent the contamination of the fresh water supply by blocking the intrusion of sea water.

Anticlinal upwarping of predominantly marine sedimentary rocks, combined with associated complex faulting, provides traps for large quantities of petroleum and natural gas. The cumulative production of more than a dozen oil fields along the zone exceeds 2.5 billion barrels of oil. Some of the fields have been producing for 45 to 50 years.

The Newport-Inglewood structural zone, commonly referred to as the Inglewood fault by seismologists, is seismically active. The largest and most destructive of the numerous earthquakes that have occurred along the zone during historic time was the Long Beach earthquake of March 10, 1933. The epicenter of this 6.3 magnitude shock lay offshore near Newport Beach whereas the aftershock activity extended along the zone northwestward to Signal Hill. Most of the 120 deaths and more than $40 million in damage resulted from the failure of inadequately constructed buildings due to strong seismic shaking of the weak alluvial materials upon which they were built. Notable among the lesser shocks also discussed in this review are the 1920 Inglewood earthquake (4.9 magnitude), and some during the 1940s with which was associated subsurface faulting that damaged oil wells in the Dominguez and Rosecrans oil fields.

No surface faulting along known faults has been observed resulting from historic earthquakes. Surface geologic effects of earthquakes include: surface cracking of alluvial materials due to lurching or settling; development of mud or sand craters where water has been ejected during a shock; landslides or rockfalls from sea cliffs and roadcuts; elevation changes, both positive and negative; changes in the level of the water table in wells; and disruption of structures built on or in the ground such as pipelines, roads, and bridges.

Differential subsidence is associated with at least three of the oil fields along the zone; Inglewood (totals about 5.6 feet); Long Beach (totals about 2.0 feet); and Huntington Beach (totals about 5.1 feet). Surface faulting, in the form of earthcracks, appears to be related to subsidence in the Baldwin Hills. Failure of the Baldwin Hills reservoir in 1963 has been attributed to displacement across earthcracks.

The *en echelon* arrangement of the uplifts along the zone, combined with evidence for right-lateral strike-slip offsets along some of the longer exposed or near-surface faults, has led many to postulate that the aligned structures are the result of deformation at depth along a through-going strike-slip fault. First-motion studies of earthquakes tend to support the concept of a right-lateral fault at the depth of origin of earthquakes. Near the surface, however, the picture is complicated locally by evidence for normal, reverse, and left-lateral faulting.

This paper contains speculations on the significance of the abrupt change in trend of the zone north of Dominguez Hill, which leads to the inference that the Newport-Dominguez-Playa del Rey trend may be the major structure with the Dominguez-Baldwin Hills reach considered an offshoot of it.

The nature, extent, and direction of continuations of the zone beyond its known limits within the Los Angeles basin are discussed. Based upon the review of all information currently available, it is tentatively concluded that the portion of the zone north of the Baldwin Hills curves toward the west of the Cheviot Hills oil field and is overridden by northward-dipping reverse faults of the Santa Monica Mountains frontal fault system.

Southeast of Newport Beach, where the Newport-Inglewood structural zone trends out to sea, the continuation of the zone can be inferred to extend as far south as Laguna Beach on the basis of the locations of epicenters. Farther to the southeast, between Laguna Beach and Oceanside, recent intensive subbottom profiling surveys reveal the presence of numerous faults, one of which has been called the South Coast Offshore fault. This feature can be traced for 40 miles approximately coinciding with the edge of the continental shelf 2 to 7 miles offshore. The known and inferred similarities between the onshore Newport-Inglewood structural zone and the South Coast Offshore fault provide a cogent argument for concluding that the Newport-Inglewood zone does extend offshore parallel to the southern California coast and that the South Coast Offshore fault is a continuation of the Newport-Inglewood zone.

INTRODUCTION AND PURPOSE

The Newport-Inglewood structural zone of folds and faults forms a northwesterly trending line of gentle topographic prominences that extends about 40 miles from Newport Mesa to the Cheviot Hills along the western side of the Los Angeles basin (plate 1; figure 1). This belt of domal hills and mesas, formed by the folding and faulting of a thick sequence of sedimentary rocks, is the surface expression of a zone of deformation that has been given various names by different workers. Petroleum geologists, reflecting their interest in the anticlinal structures that provide traps for oil, usually refer to the zone as the "Newport-Inglewood uplift" or the Newport-Inglewood zone of flexure. Structural geologists, seismologists, and ground-water geologists most often refer to the zone as the "Newport-Inglewood fault zone" or simply as the "Inglewood fault." In this paper, the simple nomenclature--the Newport-Inglewood structural zone--which refers to all structural aspects as well as surface expressions of this many-sided feature, will be used.

The presence of the Newport-Inglewood structural zone within the populous Los Angeles area has both favorable and unfavorable aspects. Numerous structural traps produced by deformation along the Newport-Inglewood zone contain large quantities of petroleum, which is of primary importance from an economic standpoint. Another economically important aspect of the zone that may be considered a benefit is the presence of certain fault planes along the zone, which serve as effective barriers to the infiltration of sea water into the severely downdrawn ground-water reservoirs of the coastal plain. These barriers also act as dams for fresh water on the landward side of the zone, thereby raising ground-water levels, which both enlarges the effective ground water reservoir and makes the water more easily accessible. This last feature is perhaps the first aspect of the Newport-Inglewood structural zone to be utilized by early settlers and farmers of the region.

There is abundant seismic evidence that the zone is tectonically active; thus, the surrounding metropolitan area is subject to certain risks. In an area of dense population, intensive industrial activity, and active exploitation of petroleum resources, the threat posed by even moderate earthquakes makes it imperative that planners and designers be able to easily obtain information about this dominant structural feature and its many aspects.

The spatial association of actively subsiding areas within portions of the zone, whether due to withdrawal of fluids or tectonism or a combination of both, also presents special problems to builders. The fact that much of the area along the zone is only a few feet above sea level increases the severity of this problem.

It is the purpose of this study to review all aspects of the geology of the Newport-Inglewood structural zone and to summarize the earthquake history. A major portion is concerned with an evaluation of the potential geologic hazards associated with future activity along the zone and the effects of earthquakes, subsidence, and such related phenomena as tsunami, flooding, landsliding, etc.

Some of the many as yet unanswered questions about the zone include: *How long is it and where and what are its "ends" like? How does the zone relate to other major structures in southern California? What is the amount and type of displacement that has taken place along the zone?* This report includes speculations about some possible answers to these questions. Ultimately, it is hoped that such speculations will provide guidelines for making some predictions about future activity along the zone.

DESCRIPTION OF THE ZONE

The term "Newport-Inglewood structural zone" is used in several contexts. Included herein are descriptions of the landforms that give topographic expression to the zone, a tabulation and comparison of the major faults associated with local structures along the zone, a summary of the petroleum geology, and a summary of the investigations of the ground-water geology in the vicinity of the zone.

Physiographic Features

It is the easily observable alignment of hills and mesas (figure 1) from Newport to north of Inglewood that first suggested and still supports the concept that the uplifted features are related to a common, linear, underlying structural element which has been called the "Newport-Inglewood fault." Although the nature and, indeed, the existence of this "fault" is uncertain, there is no doubt that the landforms do lie in a remarkably straight line. The landforms themselves have resulted from a combination of different rates of uplift and the effects of different agents of erosion at various localities along the zone. Particular emphasis is placed upon the effects of faulting on these landforms. Numerous topographic profiles which transect the uplifts along the zone were prepared as an aid to discussion. Land-surface profiles with highly exaggerated vertical scales extending the length of the zone can also be found in Poland *et al.* (1956, plate 2) and Poland *et al.* (1959, plate 3). Excellent detailed descriptions of the landforms are also included in these U.S. Geological Survey Water-Supply Papers (Poland *et al.*, 1956; 1959) and in publications of both State and local agencies involved in ground-water and flood control studies along the zone.

CHEVIOT HILLS

The Cheviot Hills are somewhat circular in plan except for a south-trending projection that extends to Venice Boulevard. Late Pleistocene marine deposits are exposed on the surface of these low, rolling hills which range in elevation from 175 to 250 feet. Except in the vicinity of Century City, these are completely surrounded by south- or east-sloping alluviated terrain. Due to the fact that they lie along the line of uplifts which defines the Newport-Inglewood structural zone, they have been considered as part of the zone. They overlie the Cheviot Hills oil field. The name Cheviot Hills is preferred over the name Beverly Hills (Poland *et al.*, 1956; 1959) because there is good evidence that the Newport-Inglewood structural trend does not underlie the old Beverly Hills oil field as was once assumed but veers, instead, westward in the vicinity of the Cheviot Hills oil field (Crowder, 1968). Poland *et al.* (1959, p. 76) tentatively extended the Inglewood fault (see below, Baldwin Hills) northward across Ballona Creek and suggested that it lay along an eastward-facing escarpment in the vicinity of Beverly Drive and Hillsboro Avenue in the Cheviot (Beverly) Hills. A discussion of this extension appears in the section dealing with the northern end of the Newport-Inglewood zone. The surficial geology of this area has been mapped by Castle (1960b), and the Pleistocene paleontology and stratigraphy of sites in the Cheviot Hills has been studied by Rodda (1957).

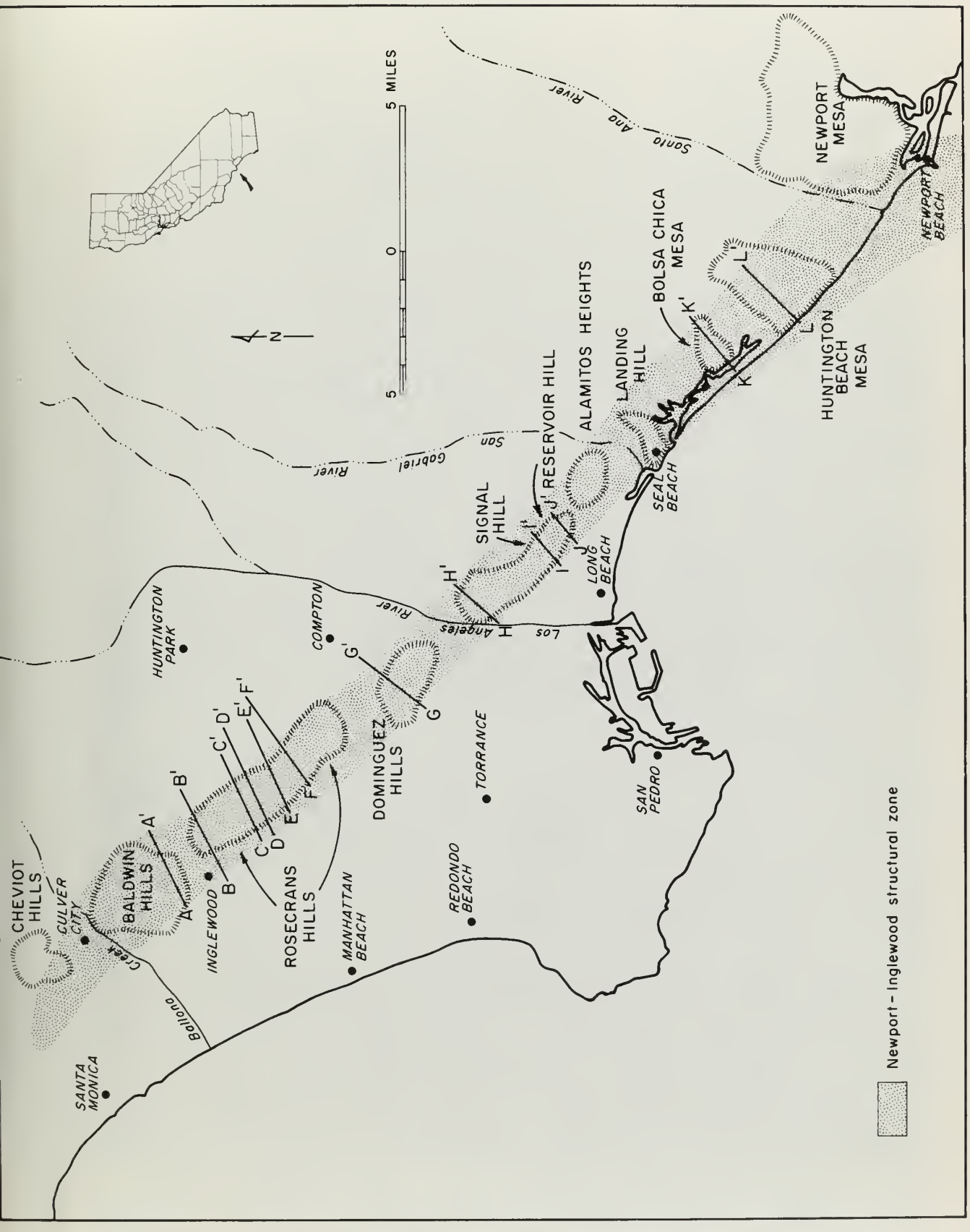


Figure 1. Hills and mesas along the Newport-Inglewood structural zone, southern California.

BALDWIN HILLS

The highest elevation of any uplift along the Newport-Inglewood structural zone is attained by the Baldwin Hills, which rise 511 feet above sea level. There is about 400 feet of relief between the summit of the hills and the Ballona Creek valley to the north. The morphology of the Baldwin Hills has been concisely described by Poland *et al.* (1956, p. 19):

> Roughly linear scarps constitute the outer faces on the west, north, and east, and these are pierced by numerous valleys sharply incised and reaching headward to the very center of the hill mass, with flat-topped ridges intervening. On the south, however, the hills descend ramplike to the adjacent lower terrane where the surface is also incised and the flat ridge tops and southward-sloping ramps are parts of a land surface initially continuous, gently arched from east to west, and plunging to the south. This is a segment of the late-Pleistocene land surface, uplifted, tilted southward, and warped by earth movements.

Photo 1. Oblique aerial photograph looking north at the central graben along the Inglewood fault in the Baldwin Hills and Inglewood oil field. Labeled localities: (A) Baldwin Hills reservoir site and breached dam; (B) Slauson Avenue; (C) LaBrea Avenue; (D) La Cienega Boulevard; (E) Stocker Street; (F) Ballona Creek channel; (G) Santa Monica Mountains. *Photo from the Spence Collection, University of California at Los Angeles taken February 3, 1967. Faults from geologic map of Baldwin Hills by R. O. Castle, 1960a.*

Photo 2. Oblique aerial photograph taken November 25, 1934, looking southward across Inglewood Park Cemetery and the future site of the Forum and Hollywood Park race track. This old photo reveals the prominent southwest-facing scarp of the Potrero fault better than modern pictures do because the intensive urbanization of much of this area obscures the delicate topographic features controlled by the underlying geology. *Photo from the Spence Collection, University of California at Los Angeles.*

The central portion of the Baldwin Hills is transected by a graben (photo 1). The eastern side of this depression is bounded by a west-facing fault-line scarp ranging in height from 75 to 150 feet. This scarp is the surface expression of the Inglewood fault (Driver, 1943, p. 308). The most detailed geologic map to date (Castle, 1960a) depicts at least six east-west-trending cross faults offsetting the Inglewood fault (see plate 1). Topography provides only a weak basis for tracing the Inglewood fault south of Centinela Creek; therefore, opinions differ as to the projected location of the fault (compare Poland *et al.*, 1959, plate 2, with Castle, 1960a). On the southeast side of the Baldwin Hills, there is an east-facing scarp which may represent the northern continuation of the Potrero fault. This scarp is as much as 50 feet high east of Centinela School (Profile A-A').

ROSECRANS HILLS

The Rosecrans Hills (figure 1) extend for about 8 miles from Centinela Creek to the Dominguez Hills as a tract of elongate, gently rising land. According to Poland *et al.* (1959, p. 20), the crest of the Rosecrans Hills

> ...declines southeastward from an altitude of 240 feet above sea level just east of Inglewood to about 100 feet above sea level as it passes into Dominguez Hill. Its transverse profiles [Profiles B-B', C-C', D-D', E-E', F-F' herein] are all somewhat asymmetric, with flatter eastern slopes that grade imperceptibly into the central lowland and with steeper western slopes that pass into Torrance Plain. Superposed on this general form are modifying features of three types: a few headward-eroding gullies and small streams; local bulges, not of erosional origin; and at least two westward-facing fault escarpments [see Profiles]. The more prominent of the two escarpments, some 60 feet high and 2 1/2 miles long, trends N. 25° W., and opposite Inglewood it passes about half a mile west of the crest of the hills [Profiles B-B', C-C' and D-D']. To the south it appears to die out in the relatively steep western flank of the hills [Profile D-D']; to the north its alinement is prolonged in an eastward facing escarpment that bounds the most southern promontory of the Baldwin Hills [Profile A-A']. The less prominent of the two escarpments begins at the northern flank of Dominguez Hill, trends about N. 25° W. for a length of 1 1/2 miles, and is half a mile west of the crest of the hills; it is about 25 feet high to the south and dies out northward.

The steeper northern escarpment, crossing Inglewood Park Cemetery and the grounds of Hollywood Park race track, represents a fault-line scarp along the Potrero fault (plate 1; photo 2). Several cross faults have also displaced this fault (Poland *et al.*, 1959, plate 2).. The gentler southern escarpment described above lies along the Avalon-Compton fault (Poland *et al.*, 1959, p. 71). The escarpment becomes topographically indistinct just north of the intersection of Rosecrans Avenue and Avalon Boulevard. In the central part of the Rosecrans Hills, although the land surface is modified by stream erosion, there are no detectable fault scarps (Profile F-F').

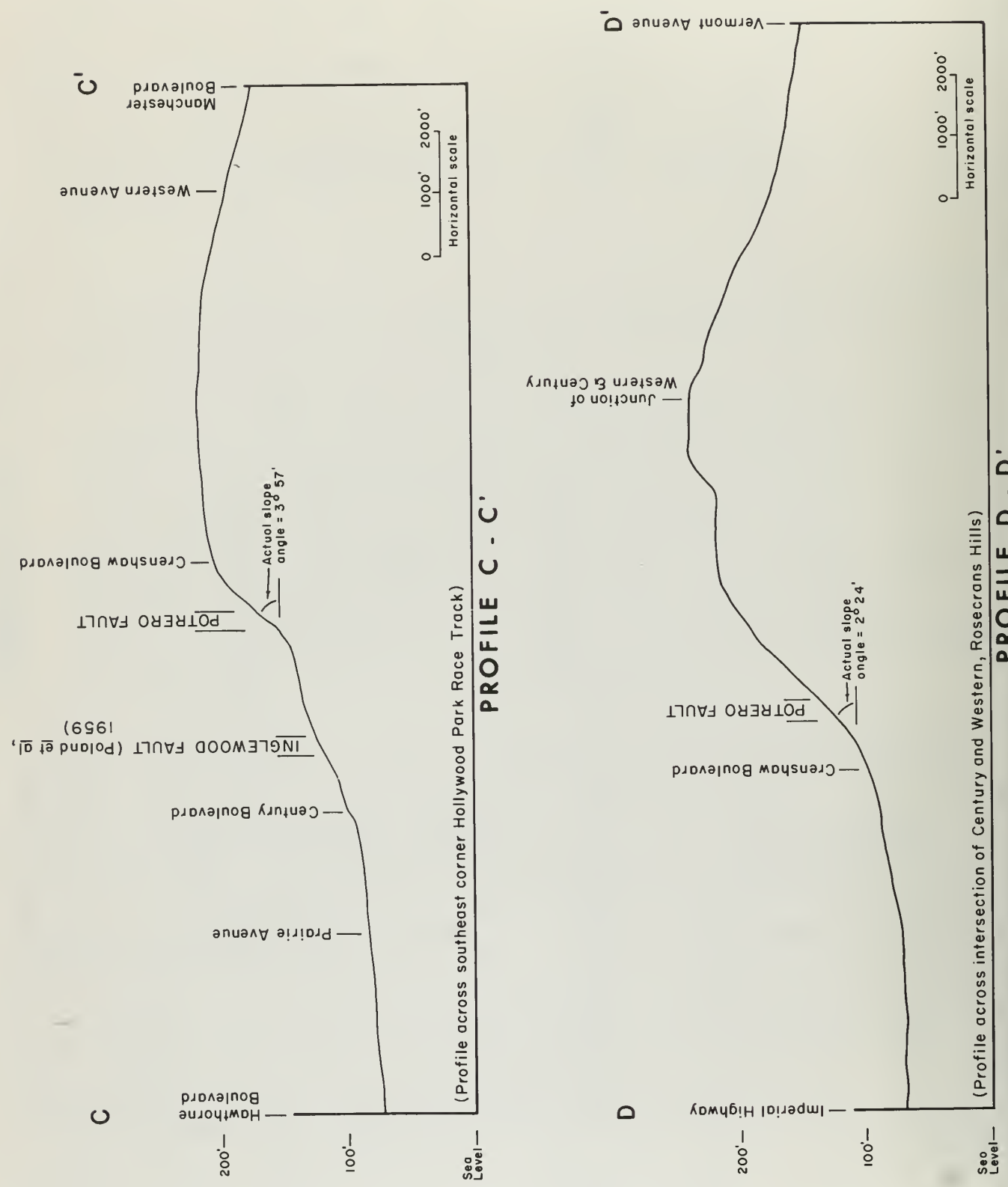
DOMINGUEZ HILLS

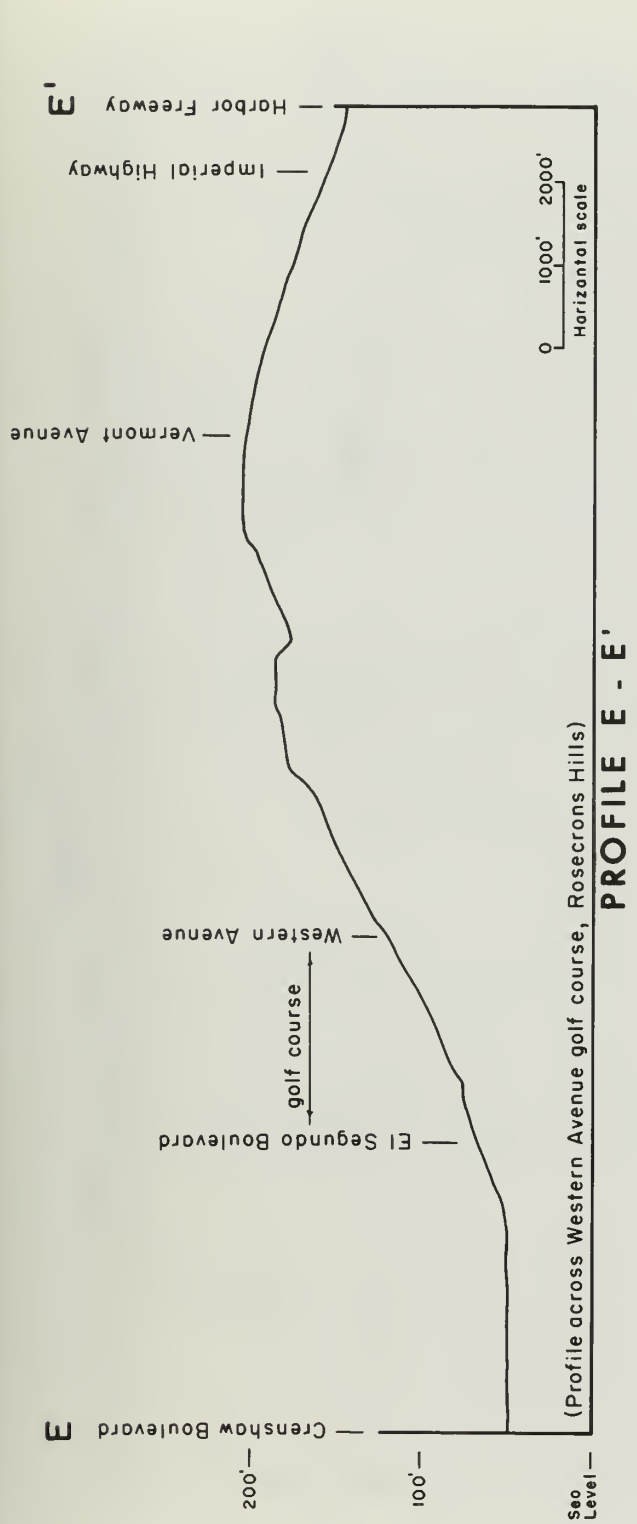
Although commonly referred to as the Dominguez Hills, the simple domal form is more properly a single hill described by Poland *et al.* (1959, p. 17) as

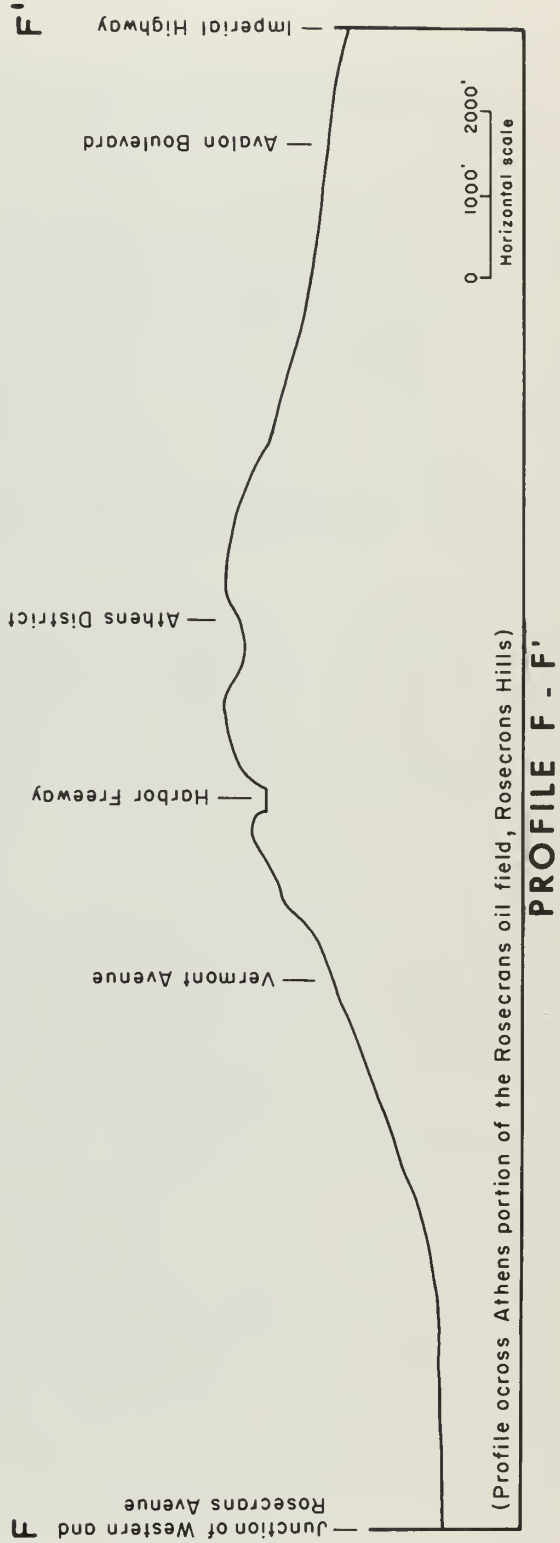
> ...a simple elliptical dome 3 miles long and about 195 feet above sea level. Like the Rosecrans Hills, it has a flatter slope on the northeast flank [Profile G-G'] and is deformational in origin; however, it is less modified by stream erosion. Its major axis trends N. 60° W., or about 20° west of the general trend of the belt of hills.

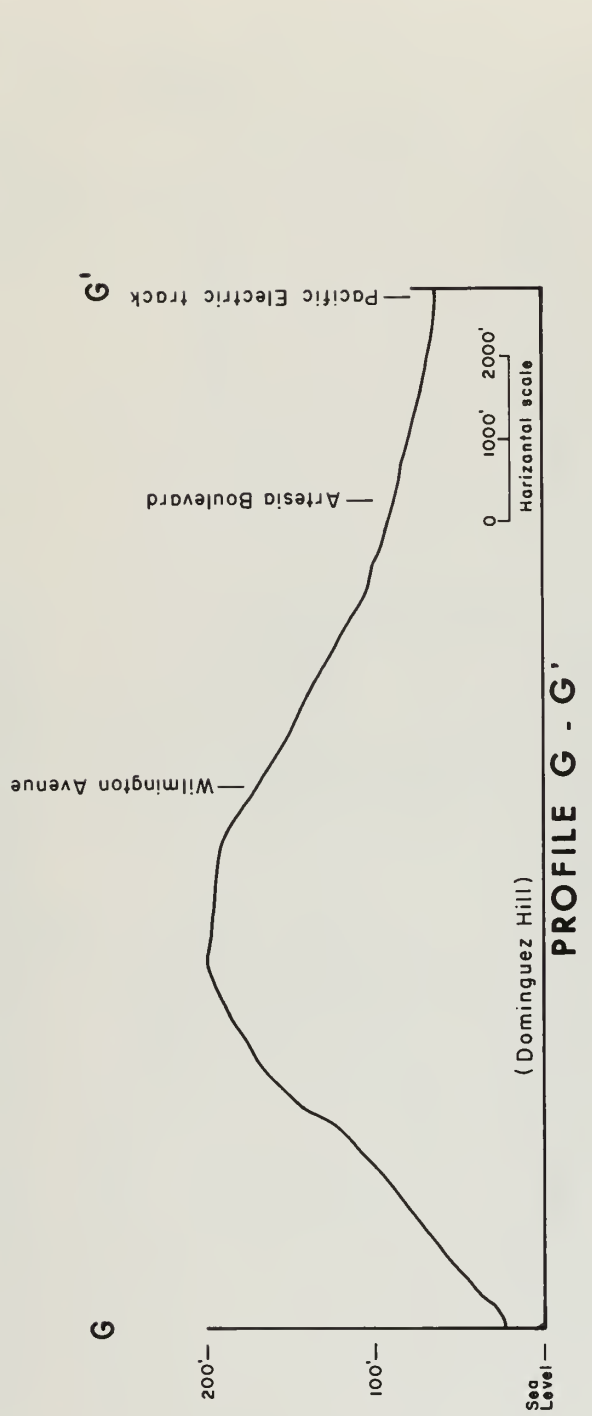
Minor faults known to exist in the underlying oil field are not exposed at the surface. However, exposures created during construction in 1969 along the east-facing bluff revealed several south-dipping reverse faults that displaced the marine sands beneath the soil near the top of the hill (photo 3).

A
A'
Lo Cienega Boulevard
Pacific Electric Track
Rogers Park
La Brea Avenue
INGLEWOOD FAULT
Centinela Avenue
Centinela School
POTRERO FAULT
Crenshaw Boulevard
Slauson Avenue
0 1000' 2000'
Horizontal scale
200'
100'
Sea Level
(Profile parallel to Hyde Park Boulevard, Baldwin Hills)
PROFILE A - A'
B
B'
Inglewood Avenue
La Brea Avenue
INGLEWOOD FAULT (Costile, 1960)
Market Street
Manchester Boulevard
INGLEWOOD FAULT (Poland et al, 1956)
POTRERO FAULT
Actual slope angle = 5° 32'
Reservoir
Crenshaw Boulevard
Florence Avenue
Mann Jr. High School
Western Avenue
0 1000' 2000'
Horizontal scale
200'
100'
Sea Level
(Profile across Inglewood Park Cemetery)
PROFILE B - B'


C
C'
Hawthorne Boulevard
Prairie Avenue
Century Boulevard
INGLEWOOD FAULT (Poland et al, 1959)
POTRERO FAULT
Actual slope angle = 3° 57'
Crenshaw Boulevard
Western Avenue
Manchester Boulevard
0 1000' 2000'
Horizontal scale
200'
100'
Sea Level
(Profile across southeast corner Hollywood Park Race Track)
PROFILE C - C'
D
D'
Imperial Highway
Crenshaw Boulevard
POTRERO FAULT
Actual slope angle = 2° 24'
Junction of Western & Century
Vermont Avenue
0 1000' 2000'
Horizontal scale
200'
100'
Sea Level
(Profile across intersection of Century and Western, Rosecrans Hills)
PROFILE D - D'


E
Crenshaw Boulevard
200'
100'
Sea Level
(Profile across Western Avenue golf course, Rosecrans Hills)
PROFILE E - E'
El Segundo Boulevard
golf course
Western Avenue
Vermont Avenue
Imperial Highway
Harbor Freeway
E'
0 1000' 2000'
Horizontal scale


F
Junction of Western and Rosecrans Avenue
200'
100'
Sea Level
(Profile ocross Athens portion of the Rosecrans oil field, Rosecrons Hills)
PROFILE F - F'
Vermont Avenue
Harbor Freeway
Athens District
Avalon Boulevard
Imperial Highway
F'
0 1000' 2000'
Horizontal scale


G
G'
200'
100'
Sea Level
Wilmington Avenue
Artesia Boulevard
Pacific Electric track
(Dominguez Hill)
0 1000' 2000'
Horizontal scale
PROFILE G - G'

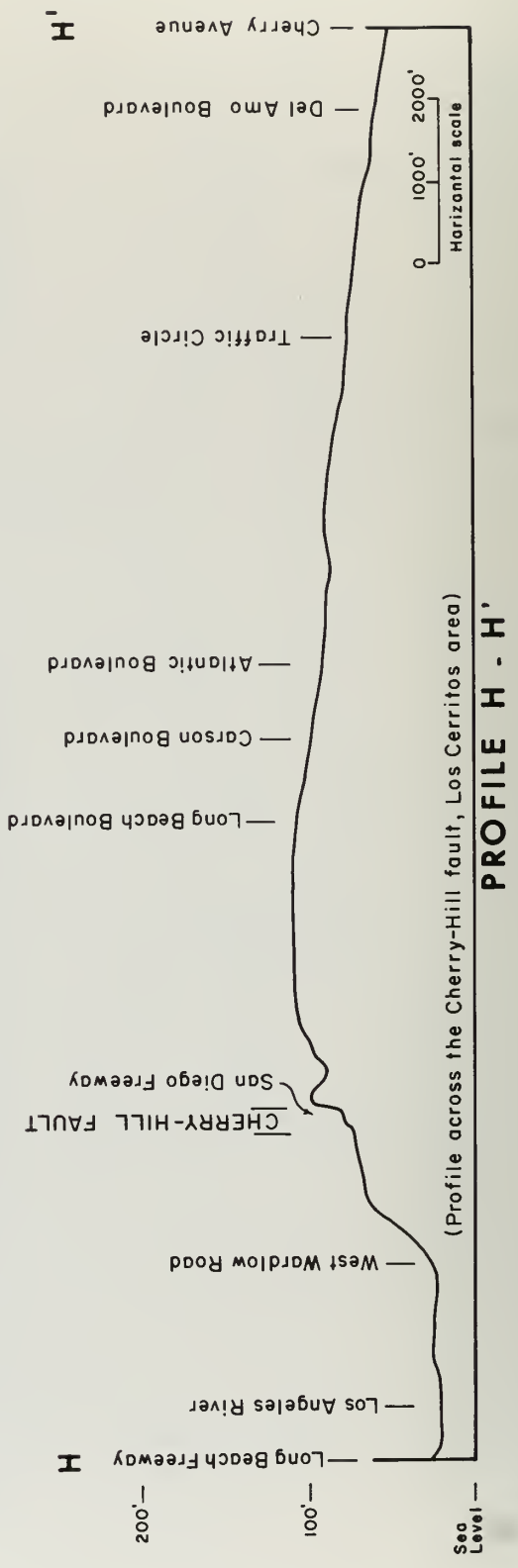

H
H'
200'
100'
Sea Level
Long Beach Freeway
Los Angeles River
West Wardlow Road
CHERRY-HILL FAULT
San Diego Freeway
Long Beach Boulevard
Carson Boulevard
Atlantic Boulevard
Traffic Circle
Del Amo Boulevard
Cherry Avenue
0 1000' 2000'
Horizontal scale
(Profile across the Cherry-Hill fault, Los Cerritos area)
PROFILE H - H'

Photo 3. East-facing exposure of south-dipping reverse faults (top center) near surface of Dominguez Hill. Faults do not extend into soil layer. *Picture taken in June 1969.*

SIGNAL HILL AND RESERVOIR HILL

Signal Hill is the most distinctive topographic feature along the entire Newport-Inglewood structural zone (photo 4). The hill rises abruptly more than 300 feet above the surrounding nearly level plain (Profile I-I'). Nearby Reservoir Hill is flat-topped and exhibits much lower relief (Profile J-J')rising only about 100 feet above the adjacent lowlands. In addition to Signal Hill and Reservoir Hill, the low, rolling topography in the vicinity of Los Cerritos, immediately southeast of the Los Angeles River, belongs to the same tectonic uplift. On the other hand, Alamitos Heights, or Bixby Ranch Hill as it is sometimes called, is included as a portion of the Seal Beach anticline (photo 5), whose surface expression has been transected by the San Gabriel River.

As is well demonstrated by Profiles I-I' and J-J', both Signal Hill and Reservoir Hill are bounded by scarplike slopes. The slope angles (see profiles) are the steepest of any uplift along the zone. The three parallel faults which lie along these slopes are, from west to east, the Cherry-Hill fault, the Northeast Flank fault, and the Reservoir Hill fault. The longest scarp lies along the Cherry-Hill (Poland *et al.*, 1956, p. 98) fault. The topographic trace of the Cherry-Hill fault extends about 4 miles southeastward from the eastern bank of the Los Angeles River as a gentle scarp across Los Cerritos (Profile H-H') along the southwestern slope of Signal Hill (Profile I-I') to Reservoir Hill (Profile J-J').

The Northeast Flank fault, along the northeast-facing slope of Signal Hill (Profile I-I'), crosses the saddle between Signal Hill and Reservoir Hill and thence along the southwestern slope of Reservoir Hill (Profile J-J') (photo 4).

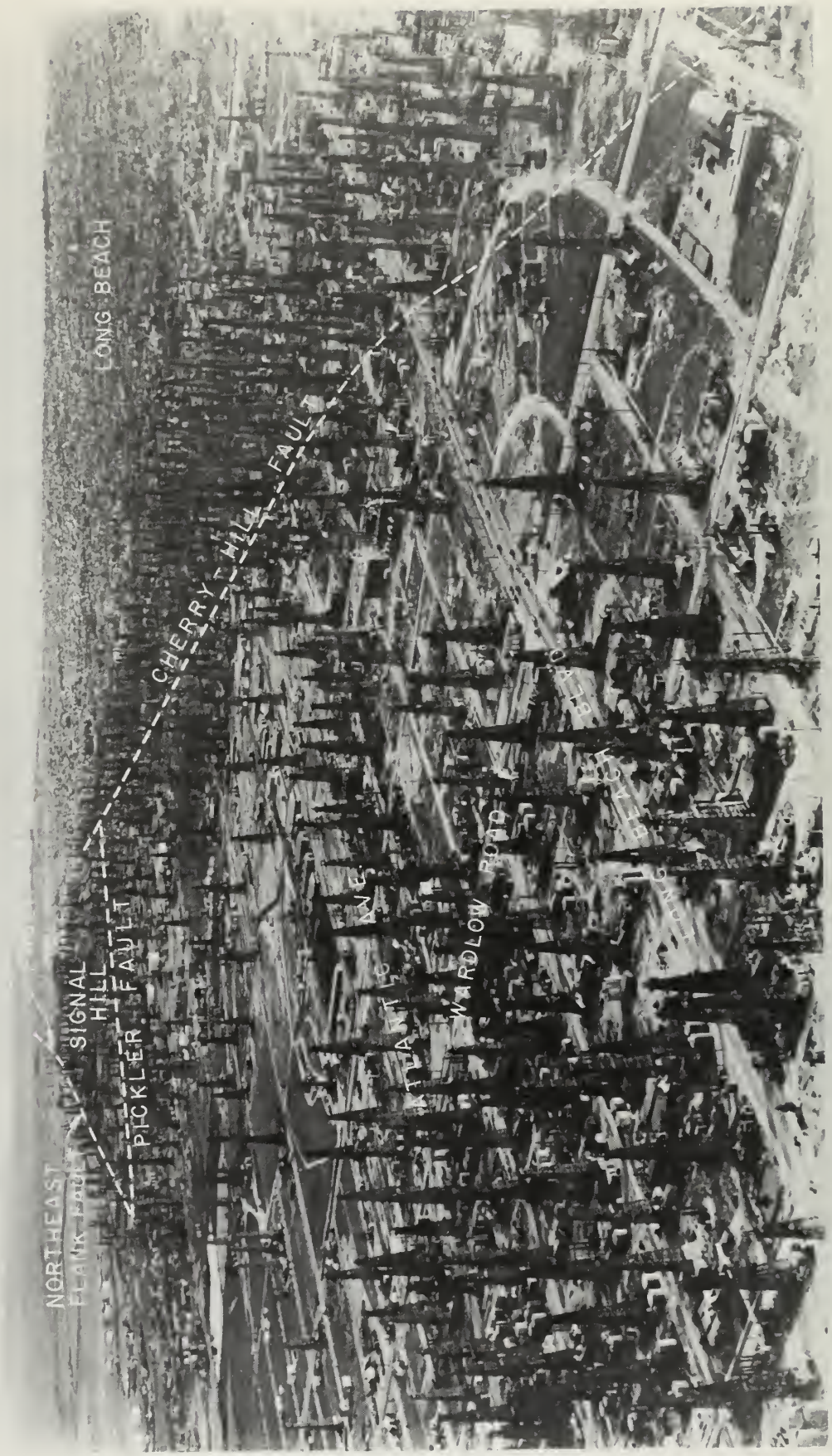
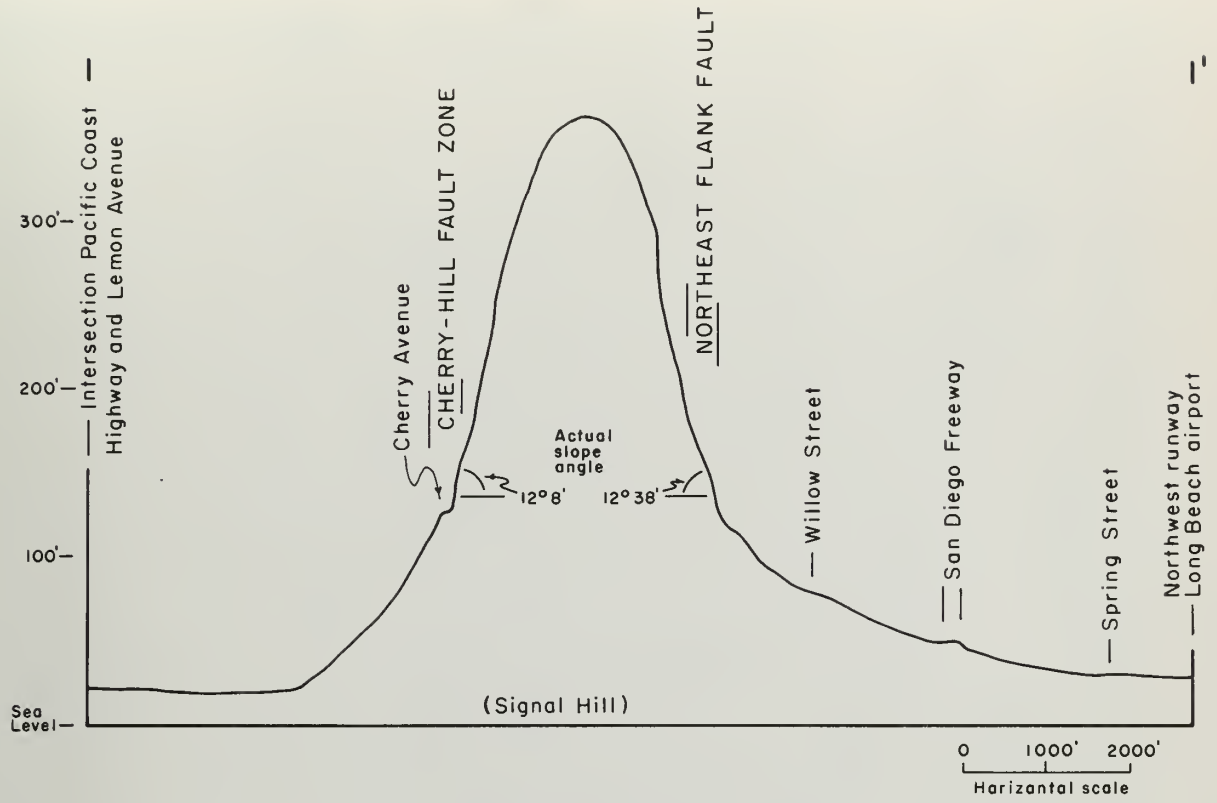
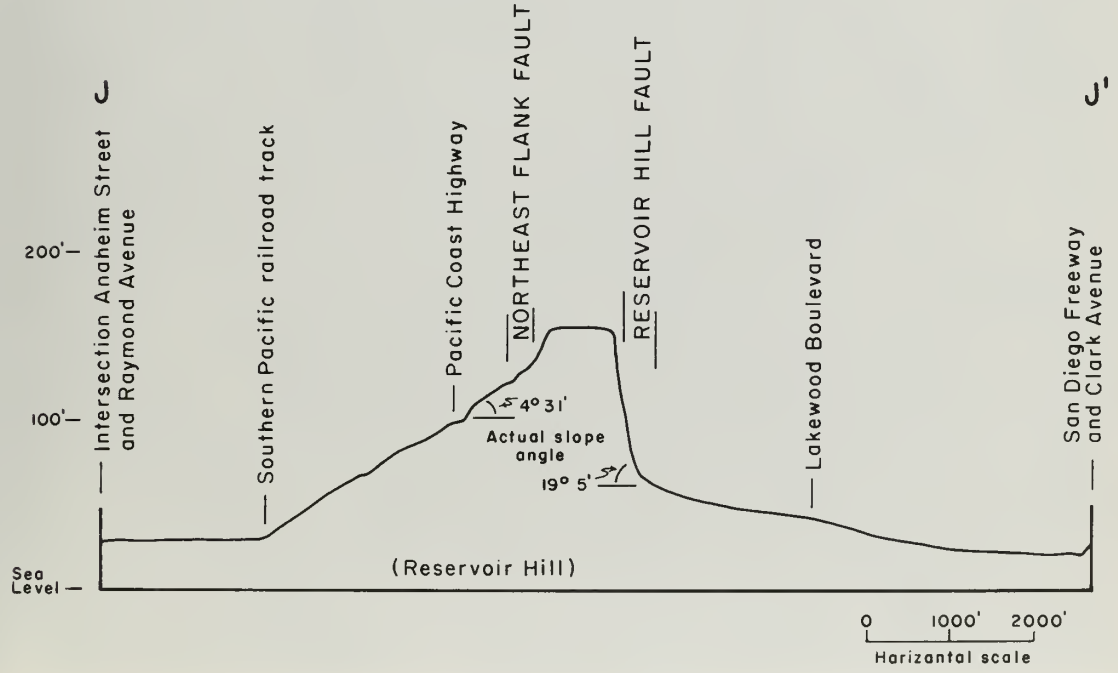


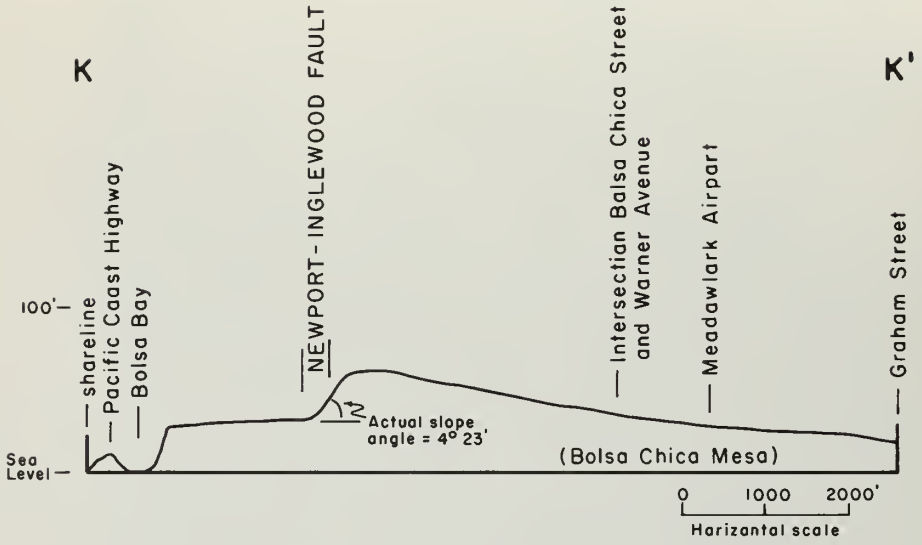
Photo 4. Looking southeastward along the strike of the Newport-Inglewood structural zone on January 25, 1931. Oil derricks of the Long Beach oil field in the foreground define limits of the Signal Hill anticline. San Joaquin Hills are about 25 miles away. *Photo from the Spence Collection, University of California at Los Angeles.*



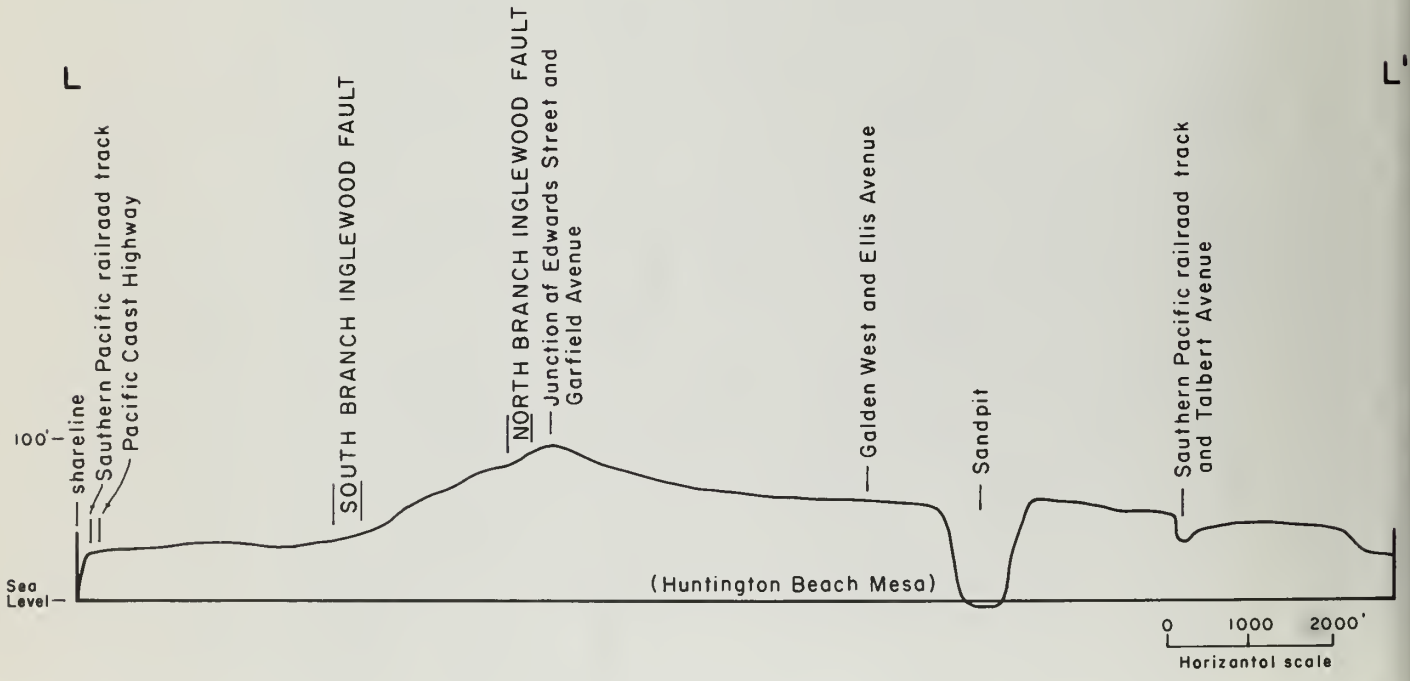
PROFILE I - I'



PROFILE J - J'



PROFILE K - K'



PROFILE L - L'

Photo 5. Looking northwestward along the Seal Beach fault from Landing Hill toward Signal Hill. The San Gabriel River flows across the eroded Seal Beach anticline and through the Seal Beach oil field. *Photo from Spence Collection University of California at Los Angeles taken October 14, 1941.*

The Reservoir Hill fault, named by Poland *et al.* (1956, p. 100), delineates the abrupt northeastern slope of Reservoir Hill (Profile J-J'). Both Bowes (1943) and Poland *et al.* (1956, p. 100) indicated that the Reservoir Hill and Seal Beach faults are one and the same.

ALAMITOS HEIGHTS AND LANDING HILL

The topographic expression of the Seal Beach dome has been breached by erosion along the San Gabriel River. Remnants of the structure at the surface are the semi-ellipsoidal, truncated landforms of Alamitos Heights and Landing Hill. Photo 5 shows the relation of these two features to the underlying structure.

Aligned swales and gentle escarpments transect Alamitos Heights and bisect Landing Hill, defining the trace of the Seal Beach fault that parallels the axial trace of the Seal Beach anticline. On opposite sides of the Seal Beach fault, the northeastern part of Landing Hill has been dropped down 15 feet relative to the southwestern part. The Seal Beach fault and the Reservoir Hill fault are shown by Poland *et al.* (1956, plate 3) as one continuous feature across the Landing Hill-Alamitos Heights-Recreation Park area.

BOLSA CHICA MESA

About 3,000 feet inland from the shoreline, Bolsa Chica Mesa is separated into two parts by a linear, west-facing escarpment. This feature is the surface expression (see Profile K-K') of the single major fault of the Newport-Inglewood structural zone that reaches the surface of Bolsa Chica Mesa. Of the two ramplike portions that dip gently toward the northwest, the inland one is 20 to 40 feet higher than the seaward one. The bluff along the southeastern edge of Bolsa Chica Mesa is an erosional feature which faces the marshes of Bolsa Bay. The northwestward dip of the mesa surfaces is attributed to the underlying northwestward-plunging Huntington Beach anticline.

HUNTINGTON BEACH MESA

The surface of Huntington Beach Mesa is divided into three portions, the boundaries of which parallel the coastline. While not scarplike, these boundaries represent the surface expression of faults of the Newport-Inglewood zone. As can be seen in Profile L-L', the highest elevation is not bounded by an abrupt scarp but by a ramplike landform. This high point is one of a series of aligned hills along whose seaward side lies the trace of the north branch of the Inglewood fault (also called High School fault). Closer to the shore, a row of swales or minor depressions (see Profile L-L') lies along the trace of the south branch of the Inglewood fault (see California Department of Water Resources, 1966, Bull. 147-1, plate 4A). Several published maps show additional faults parallel or subparallel to these two larger faults. However, topographic expression of the lesser faults is either vague or nonexistent.

NEWPORT MESA

Newport Mesa is characterized by an upper surface sloping very gently inland from an 85 to 105 feet high cliff that faces the sea along its southern edge. The Newport-Inglewood structural zone trends out to sea beneath the southwestern corner

of the mesa. The surface of the mesa is essentially a surface of marine planation that has been correlated with the lowest terrace level on the San Joaquin Hills to the east across Newport Bay (Poland *et al.*, 1956, p. 27). The landward tilt of the mesa surface is the southernmost on-land expression of deformation along the Newport-Inglewood structural zone.

Major Faults

The major faults along the Newport-Inglewood structural zone have been located as a result of intensive studies of the various uplifts during exploration for oil or investigation of ground-water barriers (plate 1). The characteristics of each of these faults are summarized in table 1.

Most of the major faults listed in table 1 are expressed at the surface as topographic escarpments in the Pleistocene sediments. Detailed accounts of the surface traces of these faults are given in the previous section. Not all of the major faults reach the surface (for example, Dominguez "regional shear zone"). In several places, the traces of the faults are buried by Holocene alluvial materials (for example, between Huntington Beach and Newport Mesas).

This summary is intended to clarify the confusing usage of similar names for different features or, conversely, different names for the same feature. Secondly, it serves to demonstrate the differences in deformational style and magnitude of displacements associated with each near-surface fault. Because until now the similarities of the structures along the zone have been emphasized, a look at the differences is useful as an aid toward understanding the complexity of the zone. Thirdly, and perhaps most important, this review indicates that the exposed major faults are not simple segments of a continuous "master fault" (the "Newport-Inglewood fault") but are related to the local uplifts which, by their alignment, give surface expression to the zone. It has been proposed by many that, at a depth not yet penetrated by drilling, there occurs a "master fault" which underlies all of the structures along the zone and which is, ultimately, the cause of the observed alignment. Such a deep-seated fault zone probably does exist--the seismic evidence from local earthquakes indicates that there must be some such feature--but the buried fault zone may be much more complex than a single, straight fault (see page 50).

Certain general aspects of the zone are portrayed on the maps (plate 1; figures 1 and 2) and in table 1. There is a significant change in the strike of the major faults both northwest and southeast of Dominguez Hill (plate 1). The faults northwest of Dominguez Hill strike N 19° W to N 25° W whereas the faults southeast of Dominquez strike closer to N 45° W to N 50° W. Although many workers have suggested or inferred that the structures along the zone are the result of movements along an underlying right-lateral fault, table 1 shows that the latest movement on the major near-surface faults encountered along the zone is not uniformly right lateral. There are two faults at Dominguez and Seal Beach for which the evidence suggests left-lateral displacement. Estimates of the amount of right-lateral displacement, where the evidence has been quantitatively evaluated, range from 600 feet along the Townsite fault (Potrero oil field) to a suggested maximum of 6 miles along the High School fault of Hungtington Beach. Comparison of the displacements in the Inglewood and Rosecrans oil fields or the apparent sense of direction of the most recent movements in the Seal Beach and Huntington Beach or West Newport oil fields shows that there is, in detail, no simple progressive increase in total displacement along the zone.

Table 1. Major faults associated with the Newport-Inglewood structural zone.

Fault name	*Location (oil field)*	*Orientation*	*Type*	*Displacement*	*References*
"Newport-Inglewood fault"	Cheviot Hills	"Southwesterly dipping normal fault . . . west of the field"	Normal	Not available.	Crowder, 1968, p. 19
Inglewood fault	Inglewood	Strike: N 22° W Dip: 60° to 80° W	Normal and right lateral	Vertical offset—275 feet at surface, down on west; horizontal displacement as much as 1,500 feet right-lateral separation Horizontal displacement—3,000 to 4,000 feet right lateral; displacement since middle or late Pliocene time (apparent offset of structural crests on both the tops of the "Gyroidina" zone during Quaternary time, 1,500 to 2,000 feet right-lateral displacement	Driver, 1943, p. 308 Castle and Yerkes, 1969, p. 7
Potrero fault	Potrero (East Area)	Strike: N 25° W Dip: 82° SW (flatter near surface—77° SW—steepens downward)	Normal and right lateral	Vertical displacement (throw) at depth of 3,000 feet is 270 feet Horizontal displacement—right lateral-1,200-foot offset in crest of fold	Willis and Ballantyne, 1943, p. 310–311
Townsite fault may be continuous with Inglewood fault, see Poland *et al.*, 1959		Strike: N 25° W Dip: steeply east, steeper at surface than at depth	Reverse and right lateral	Stratigraphic throw 100 feet down on west 600 foot offset (right lateral) in structure contours of oil field	
Unnamed (but field is west of continuation of "Inglewood" fault as mapped in Rosecrans oil field)	Howard Townsite	Strike: N 12° W Dip: essentially vertical to steeply east on cross section A-A′, Matthews, 1954	Reverse to vertical	100 feet stratigraphic throw at depth of 8,000 feet, down on east	Matthews, 1954, p. 19
Inglewood fault (Foster, 1954)	Rosecrans	Strike: N 19° W Dip: vertical (in cross section)	Vertical or normal	Athens and central areas down on east (NE striking thrust faults dip to S common west of Inglewood fault)	Foster, 1954
Inglewood fault (California Division of Oil and Gas, oil and gas fields of California, Part II, compare p. 646 and 648	East Rosecrans	Strike: N 19° W Dip: 80° W	Normal	Up on east	California Division of Oil and Gas, 1961, California oil and gas fields, maps and data sheets, p. 646
Inglewood fault *also called* Avalon-Compton fault (Poland *et al.*, 1959)	South Rosecrans	Strike: N 19° W Dip: vertical in cross section Strike: N 24° W Dip: unknown	Vertical or normal	Stratigraphic throw 40 feet at 7,000-foot depth, westside down—Note: Plate V of Foster (1954) is incorrect—should show west side down. Topographic offset 25 feet, west side down.	Foster, 1954 Poland *et al.*, 1959
"Regional shear zone"—"thought to be a member of the Newport-Inglewood shear zone system"	Dominquez	Strike: N 38° W Dip: 80° to 85° NE	Left lateral (Graves, 1954)	"Maximum apparent vertical throw that has been measured is 200 feet . . ." Grinsfelder, 1943 p. 318 "Main movement . . . roughly parallel with the Inglewood rift" Grinsfelder, 1943, p. 318 Effects of faulting become evident below 4,000 feet, Miocene units show greatest horizontal offset	Grinsfelder, 1943, p. 318–319 Graves, 1954, Map Sheet 32

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Table 1. Major faults associated with the Newport-Inglewood structural zone—Continued

Fault name	*Location (oil field)*	*Orientation*	*Type*	*Displacement*	*References*
Cherry Hill fault (or Cherry-Hill fault—see Poland *et al.*, 1956, p. 98) also called Signal Hill fault (Dudley, 1954)	Long Beach	Strike: N 47° W Dip: 80° NE from surface to 5,000 feet where dip flattens (Ingram, 1968) nearly vertical down to 3,500 feet and below is a thrust (Dudley 1954)	Reverse and right lateral	Vertical displacement—basement (schist) surface offset more than 4,000 feet up on northeast side Horizontal displacement of Brown zone (Miocene at depth of 4,000 feet) is 3,000 feet right lateral sense	Stolz, 1943, p. 320–324, Dudley, 1954, Map Sheet 34 Ingram, 1968 p. 5–15 Poland *et al.*, 1956 p. 98
Northeast Flank fault		Strike: N 44° W Dip: steeply SW, apparently merges with Cherry Hill fault at depth	High-angle reverse	Maximum throw 500 feet down on NE at depth of 4,000 feet	Stolz, 1943
Wardlow fault		Strike: N 60° W Dip: steeply SW at surface, apparently merges with Cherry Hill fault at depth	Normal	Down on SW, vertical displacement about 200 feet at depth of 7,000 feet (Harris, p. 76)	Ingram, 1968 Harris, 1958 p. 75–77
Wardlow-Airport fault	Long Beach (Airport Area)	Strike: N 62° W Dip: 80° NE but is actually variable in apparent dip	Reverse	Down on SW side, amount not available (compare with Wardlow fault above). (Note: arrows and stratigraphic offset do not agree.)	California Division Oil and Gas, California oil and gas fields Part 2, 1961, p. 596
Reservoir Hill fault or "Inglewood-Newport" or Seal Beach fault	Long Beach Recreation Park Area	See Seal Beach fault below	Normal	Down on NE side	Ingram, 1966, p. 67–72; Poland *et al.*, 1956
Seal Beach fault "inferred . . . to be essentially continuous with the Reservoir Hill fault" (Poland *et al.*, 1956 p. 100)	Seal Beach	Strike: N 50° W Dip: 88° NE to vertical	Normal left lateral (Zeilbauer *et al.*, 1961) right lateral (Div. Oil and Gas Data Sheet, 1961, p. 666)	"Topographic evidence and subsurface structure suggest that movement along the fault was generally in a vertical direction: it is not known to exceed 200 feet." Bowes, 1943, p. 325, 150 to 200 feet vertical displacement at depth of 4,500 feet "Late Pleistocene movements were mainly horizontal with only a small vertical component. The coastal block moved southeast and up relative to the landward block." (Zeilbauer *et al.*, 1961, Plate 1)	Bowes, 1943, p. 325–328; Zeilbauer, Burnham and Keene, 1961, Plate 1 Allen and Hazenbush, 1957, p. 47–50
Inglewood fault (Allen and Hazenbush)	Sunset Beach	Strike: N 44° W Dip: steeply west	Normal	Vertical displacement on Plate V of Allen and Hazenbush (1957) about 375 feet down on west at depth of 5,000 feet "With the exception of the Inglewood fault, few faults extend up into the Pliocene beds and those that do are minor in displacement." (Allen and Hazenbush, 1957)	
Newport-Inglewood fault—Bolsa-Sunset area—locally known as the Seal Beach fault or High School fault		Strike: N 44° W Dip: steeply southwest	Right lateral, Bolsa Gap has shear zone 900 feet wide with 3 parallel faults	"Amount of horizontal displacement among water-bearing deposits within the study area is indeterminable." (p. 35, DWR Bull. 63-2) Land surface of Bolsa Chica mesa up on E 20 to 40 feet Well logs indicate maximum apparent vertical displacement 35 feet in upper Pleistocene beds and 50 feet among lower Pleistocene beds, Bolsa Chica Mesa	California Dept. Water Resources Bull. 63-2, 1968 Bolsa-Sunset Area

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Table 1. Major faults associated with the Newport-Inglewood structural zone—Continued

Fault name	*Location (oil field)*	*Orientation*	*Type*	*Displacement*	*References*
High School (Inglewood) fault "possibly southeast extension of the main Seal Beach fault" (Willis, 1958)		Strike: N 45° W Dip: steeply southwest	Right lateral "deep-seated shear zone"	"The deep-seated shear may come up to the level of the lower "C" shale about 6,000- to 7,000-foot depth because there is a change in section across the southwest flank of the main zone fold which probably marks the position of the shear." (Willis, 1958, p. 141)	Willis, 1958 p. 135–141
Inglewood fault (High School fault)	Huntington Beach	Strike: N 45° W Dip: vertical to very steeply west	Right lateral "hinge fault"	"Vertical displacements across the Inglewood fault system vary from 1,200 feet at the southeast end of the field to none near the center of the field. Right lateral horizontal movements may total six miles since middle Miocene time." (p. 17) . . . "relative dip-slip movements have been predominantly positive on the south block." (p. 18)	Hazenbush and Allen, 1958, p. 17–19
North Branch Newport-Inglewood fault		Strike: N 45° W Dip: essentially vertical near surface	Right lateral	"Within upper Miocene strata, apparent vertical displacements along the North Branch of the Newport-Inglewood fault may be as great as 2,000 feet. Horizontal movements may total six miles since middle Miocene time, according to studies of the Huntington Beach oil field conducted by other agencies." (p. 20) Up to 300 feet vertical displacement of lower Pleistocene San Pedro strata, one-half mile or more of horizontal separation in the San Pedro Formation	California Dept. Water Resources Bull. 147–1, 1966
South Branch Newport-Inglewood fault		Strike: N 45° W Dip: essentially vertical near surface	Normal and right lateral	Down on west; amount of displacement not available	
North Branch Inglewood fault	West Newport	Strike: N 45° W Dip: 82° W near surface	Normal and right lateral	"Vertical displacements across the system as great as 2,000 feet. Horizontal movements of large magnitude have also occurred." (p. 16)	Hunter and Allen, 1965, p. 16–17 Allen and Joujon-Roche, 1958, p. 142–144
North and South Branches of Newport-Inglewood fault (see above under Huntington Beach)		South Branch merges with North Branch west of Huntington Beach mesa. South Branch changes dip between 2,000 and 3,000 feet down	Right lateral		California Dept. Water Resources Bull. 147–1, 1966
Inglewood-Newport fault	Newport	Series of right lateral faults	Series of right lateral faults	North Branch Inglewood fault trends out to sea beneath SW corner Newport Mesa—oil fields lie north of this fault	Ingram, 1968, p. 43

The variability in estimates of magnitude of displacement and the dissimilarities in inferred sense of displacement for adjacent surface structures along the zone emphasize the problems involved in interpreting the movement along a deep-seated shear zone. There is abundant information in most of the oil fields that allows the history of deformation to be traced back to the middle Miocene. Furthermore, subsurface structural data indicate that deformation has been more or less continual since that time in all of the structures. This being the case, the dissimilarity in histories in the various fields indicates a much more complex pattern than that of simple right-lateral shear along a single deep-seated zone. The effects of impinging or diverging structural trends (for example, the Dominguez-Playa del Rey trend) on the Newport-Inglewood structure are probably the best examples of this complexity.

The structural evolution of the complicated Huntington Beach and West Newport oil fields may have been influenced by the uplift of the San Joaquin Hills, rather than simply controlled by movements along the Newport-Inglewood structural zone. In addition, the trend of the offshore portion of the Huntington Beach field and the Wilmington-Torrance fields suggests that these structures are related to a zone that diverges from the Newport-Inglewood zone (see page 50).

HISTORY OF INVESTIGATION AND RECOGNITION

Ground-Water Geology

Interest in the geology of the western portion of the Los Angeles basin reflects the cultural activities and land-use priorities at the time of the investigation. At the beginning of the twentieth century, the residents of the Los Angeles basin were engaged primarily in agricultural activities. Accordingly, interest in ground-water levels and supplies spurred geological studies of this area. What is probably the earliest reference to the Newport-Inglewood zone (although not yet named) was made by Mendenhall (1905, p. 14-15):

> The interrupted ridge which extends northwest from Huntington Beach to the vicinity of Palms divides the coastal plain into an eastern and a western portion. Of these, the eastern portion has much the greater area. It includes the bigger part of the Downey, Anaheim, and Santa Ana quadrangles, while the western section occupies much of the Redondo quadrangle and a part of the Santa Monica quadrangle. The ridge which separates these two sections is not a surface feature merely. It seems to be the surface expression of a broad fold in the sands and clays of the coastal plain--a fold that acts as a dam to waters seeking a way seaward beneath the surface in order to pass the obstruction. In consequence, ground water levels are much higher above this ridge than below it, as would be true of a surface dam, and the chief artesian basin of the coastal plain, as indeed, of southern California owes its existence to it.

Even though most of the inhabitants of the area adjacent to the Newport-Inglewood zone are no longer involved in agriculture, they still depend upon local sources of water for some of their industrial and domestic needs. Accordingly, studies of the hydrology and shallow-depth geology have been carried out by many agencies whose task it is to find and provide adequate, usable water to this area. Among the studies, those of the Water Resources Division of the U.S. Geological Survey have been prominent in locating, defining, and delineating the ground-water reservoirs near the zone. Publications of this group start with Mendenhall's Bulletin 139 (1905), but the most detailed reports were those produced under the direction of J.F. Poland. These latter publications include Water-Supply Papers 1109 (1956), 1461 (1959), and 1471 (1959) that deal specifically with the geology of the Newport-Inglewood structural zone along its entire length within the Los Angeles basin.

Although the ground-water barrier effect of the Newport-Inglewood structural zone was recognized by Mendenhall (1905), he was not concerned at that time with the importance that the structure plays in restricting the intrusion of salt water into fresh-water aquifers. During the 1930s, the California Department of Public Works, Division of Water Resources, initiated the "South Coastal Basin Investigation." Most of the results of the studies of the ground-water quality, storage capacity, and salt-water intrusion were not published but appeared in office reports. An exception to this is Bulletin 45 by Eckis (1934). Accompanying this report is the most detailed geologic map (scale 1 inch equals 2.3 miles) to be published on the region up to that time. Eckis was concerned primarily with the geologic conditions that affected the ground-water storage capacity of basins in this portion of southern California. He dealt only briefly with the barrier to sea-water intrusion effected by the presence of the Newport-Inglewood structural zone.

In recent years, as the rate of withdrawal of fresh water has increased from the ground-water reservoirs, much attention has been focused on the intrusion of sea water into the fresh-water-bearing aquifers. The studies of the U.S. Geological Survey, referred to above, deal, in part, with this problem. However, the most detailed studies

of sea-water intrusion landward of the Newport-Inglewood structural zone have been made by other agencies having the responsibility of monitoring and delineating areas of contamination of the fresh-water supply. Personnel of the California Department of Water Resources (1966; 1968) have studied intensively the near-surface geology of the Santa Ana River Gap and the Bolsa-Sunset area in Orange County. Their reports provide detailed accounts of the near-surface faults that act as barriers to the landward intrusion of sea water into fresh-water aquifers. In addition, the Los Angeles County Flood Control District (Zeilbauer *et al.*, 1961; Zeilbauer *et al.*, 1962) has made detailed studies of two other gaps, Alamitos Bay and Dominguez Gap, that lie along the Newport-Inglewood structural zone.

All of these studies emphasize the dominant role played by faults acting as barriers to sea-water intrusion along the Newport-Inglewood zone. The methods of investigation usually employed by ground-water geologists and hydrological engineers include the drilling of water wells specifically for the purpose of deciphering the stratigraphy of the shallow-depth aquifers. The detailed information obtained through such studies is necessary for correlation of thin or minor units across structural discontinuities (that is, fault zones). These data also provide the best information on the age of the most recent deformation along any faults encountered.

A direct result of these intensive investigations has been the generation of a large amount of data covering the geology of the shallow-depth (down to 400-500 feet subsurface) fresh-water-bearing units along the Newport-Inglewood structural zone. It must be emphasized that extrapolations from abundant but shallow-depth data can lead to a simplified picture of the over-all history of the zone. For instance, it must not be assumed that the numerous faults shown on the Geologic Map of California (Rogers, 1965; Jennings, 1962; Jennings and Strand, 1969) along the Newport-Inglewood structural zone are one and the same with the master fault or faults at depth along which earthquakes take place. These faults, as shown, were mapped or inferred by ground-water geologists. Except for the few that are encountered in oil wells, the down-dip extensions of these faults are unknown.

Petroleum Geology

The early years of the twentieth century witnessed a flurry of activity in the search for petroleum deposits in the Los Angeles basin. Even though Mendenhall (1905, p. 15) clearly described the subsurface aspects of "the broad fold in the sands and clays of the coastal plain" by 1907, the significance of this structure was not recognized for its oil-trapping possibilities. This is indicated by the comments of Eldridge and Arnold (1907, p. 197) regarding possible oil fields in the Los Angeles basin.

> Outside of the . . . Los Angeles oil field there is little or no evidence of renumerative oil deposits in the immediate vicinity of Los Angeles. Were it not for the great thickness of Pleistocene sand and gravel, which covers the great Los Angeles Plain from the Santa Monica Mountains and Raphetto [sic] Hills to the ocean, it would be more than likely that productive territory could be developed over this plain. At least it is almost certain that the oil-bearing strata underlie it, but whether or not the structural conditions are at any place conducive to the accumulation of gas or oil in paying quantities can be determined only by costly exploitation with the drill.

These authors were apparently unaware of the drilling that had been done in the Rosecrans Hills more than 20 years before their paper was written. A reference to a well in the "Rosecranz Tract" was included by W. A. Goodyear in his contribution to the Seventh Report of the California State Mineralogist (1887, p. 79). This 85-foot well provided its owner with gas for domestic use.

In the first decade of the twentieth century, several wells were drilled at different places along the uplift by those searching for oil (Prutzman, 1913, p. 332). Prutzman points out that about a dozen wells were drilled along the uplift, mostly in the vicinity of Howard Summit and the Rosecrans tract, and that there were "showings of oil" or even a slight production of gas in most of these wells. Referring to the "oil showing" Prutzman says (1913, p. 332-333):

> Even these slender indications are of interest in connection with the fact that these wells are located along a little ridge, perhaps 100 feet in height, a continuation of the Tijera [Baldwin] Hills. This low roll is the only interruption of the continuity of the plain between Los Angeles and the ocean, and has the same position relative to the Santa Monicas as have the Coyotes to the Puente Hills. Where the summit of this raise is cut through by the Long Beach electric line, an anticlinal structure is plainly shown, and it seems strange that (as far as could be learned) no prospecting has ever been done along this ridge. It seems quite certain that, if any oil is to be found between Los Angeles and the ocean, a point along the ridge between Palms and Compton would be the most favorable place at which to drill.

In 1914, C. A. Waring (*in* McLaughlin and Waring, p. 357) postulated that the Beverly Hills oil field lies on an anticlinal ridge which "is probably the northern end of the low ridge which passes just east of Inglewood and extends southeastward through Howard Summit, Dominguez Hill and Los Cerritos [Signal Hill]." In addition, Waring (p. 315) suggested that "there are possibilities that future drilling may develop considerable areas, particularly along the series of low hills extending from Beverly to Los Cerritos, near Inglewood, Howard Summit and Dominguez Hill." Prior to 1920, drilling activity at Inglewood and the Dominguez Hills was reported upon by Kirwan (1918a; 1918b). Most of these exploratory wells were shallow, and oil production was not initiated at any of them.

Prospecting activity increased along the uplift with the result that between 1920 and 1924 most of the major fields had been discovered and were producing. Listed below are these fields and their "discovery" dates (generally considered to coincide with completion of the first producing well):

Oil field discovery dates

	Division of Oil and Gas (1961)	*Division of Mines Bulletin 118 (1943)*
Huntington Beach	June 4, 1920	May 24, 1920
Long Beach	June 25, 1921	June 25, 1921
Dominguez	Sept 1, 1923	Sept 1, 1923
Rosecrans	May 5, 1924	May 1924
Seal Beach	Sept 1924	Aug 1924
Inglewood	Sept 28, 1924	Sept 28, 1924

Naturally, the discovery of so many closely spaced oil fields along the zone helped to delineate it, both in length and width. Petroleum geologists soon developed hypotheses that accounted for the origin of the structures whose dimensions were being

revealed by drilling records. In all of these discussions, the separate oil-bearing structures were considered in relation to the Newport-Inglewood structural zone as a whole. See "History of Hypotheses on Origin and Development of Structural Features" (this paper) for detailed account of development of tectonic hypotheses.

Workers interested in petroleum geology wrote numerous papers during the 1920s and 1930s dealing with the structural history and tectonic setting of the zone. The various hypotheses developed to account for features observed and inferred about the zone are reviewed in the section on structure and tectonics. Many of the currently accepted concepts about the zone were originally proposed in those earlier papers.

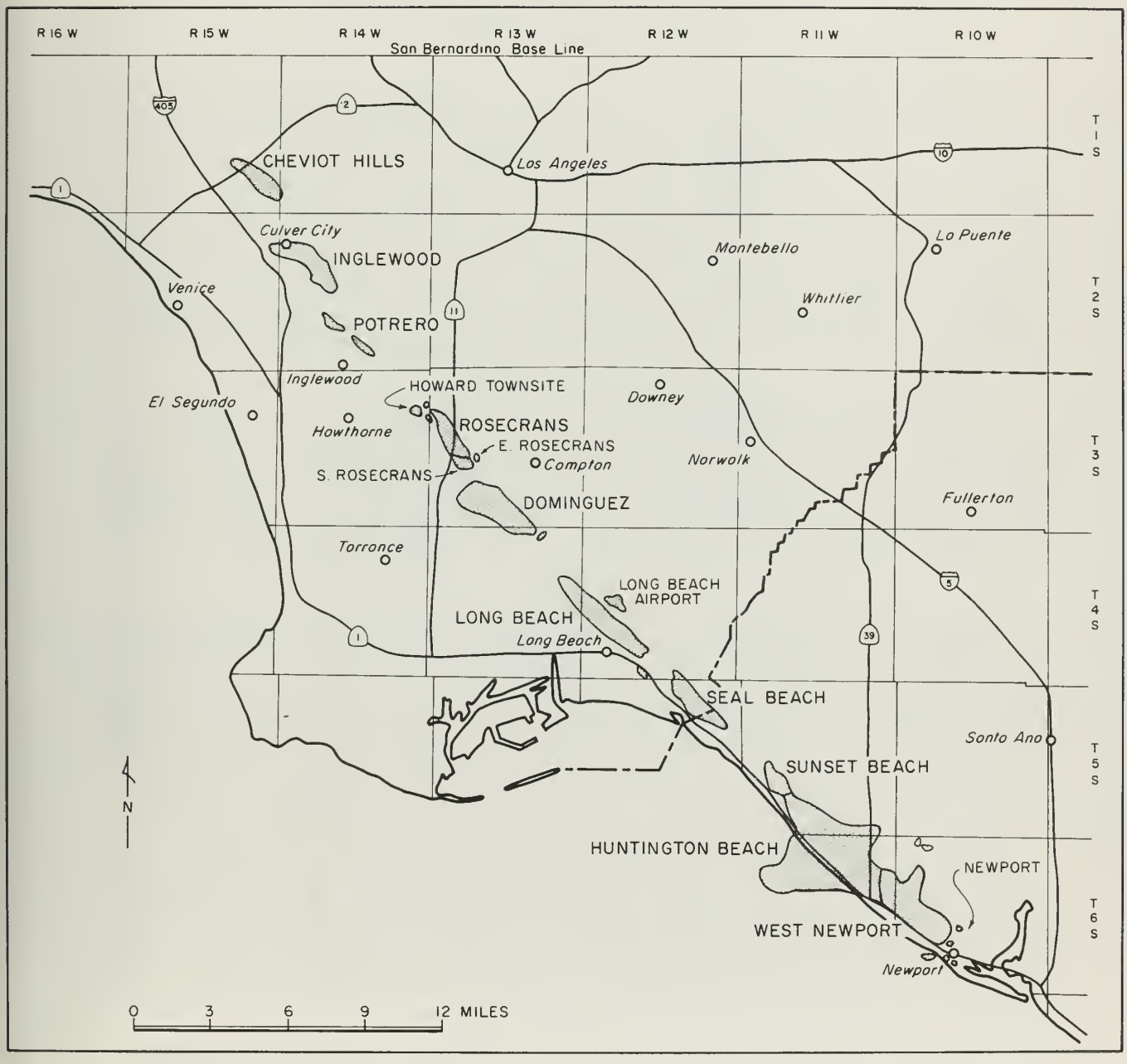

Figure 2. Oil fields along the Newport-Inglewood structural zone.

The two most important sources of data on the oil fields of the Newport-Inglewood zone are the publications of the California Division of Oil and Gas (for example, *Summary of Operations--California Oil Fields)* and Bulletin 118 (1943) of the California Division of Mines. Extensive bibliographies on the petroleum geology of most of the Newport-Inglewood oil fields are included. Other important references to the petroleum geology of these oil fields can be found in Bulletin 170 (1954) of the California Division of Mines; *in* Knapp *et al.* (1962, Cenozoic correlation section from Beverly Hills to Newport, California); and Guidebook 8 on the coastal oil fields of the Los Angeles basin by the American Association of Petroleum Geologists (1966). Figure 2, from the California Division of Oil and Gas (1969), shows the oil fields along the Newport-Inglewood structural zone.

Differential Subsidence Associated with Oil Fields

Elevation changes, revealed by comparisons of repeated leveling surveys, have long been recognized in the Los Angeles region (Grant and Sheppard, 1939; Grant, 1944). Studies of the leveling data from thousands of stations have shown that, in general, those stations in the lowland areas of the Los Angeles basin are subsiding, whereas some of the stations in the foothill areas are rising (Stone, 1961). Superimposed upon this background of regional elevation changes are local depressions, delineated by closed contours, that result from differential subsidence. Subsidence bowls are associated with the Inglewood, Long Beach, and Huntington Beach oil fields along the Newport-Inglewood zone (figure 3). In addition, minor localized differential subsidence has been documented over the Dominguez oil field (Castle and Yerkes, 1969, figure 51).

The maximum cumulative subsidence of any of the areas along the Newport-Inglewood zone is centered over the Inglewood oil field in the Baldwin Hills. A careful review of the data from leveling circuits run between 1911 and 1963 involving painstaking reduction to a common datum by Castle and Yerkes (1969) has shown that the maximum subsidence was 5.67 feet at bench mark PBM 122 located about 2,000 feet north of the intersection of Stocker Street and La Cienega Boulevard.

Grant (1944, figure 9) presented a map showing an elliptical subsidence bowl, 4 miles long by 2 3/4 miles wide, whose longer axis parallels that of the elongate Long Beach oil field at Signal Hill. Near the center of the oil field, the maximum subsidence was at least 0.40 foot from 1925 to 1930. At present, the outline of the differential depression (figure 3), in which the Long Beach oil field lies, is complicated because of the subsidence associated with the Wilmington (Gilluly and Grant, 1949; Grant, 1954) and Torrance (Golze, 1965, p. 100) oil fields. Maximum subsidence for the interval 1928-1965 over the Long Beach oil field exceeds 2.0 feet (Mayuga, 1965, figure 5).

Between 1932 and 1941, certain benchmarks in the vicinity of Huntington Beach subsided as much as 1.18 feet (Gilluly and Grant, 1949, p. 526). "Maximum subsidence occurred along the stretch of Pacific Coast highway within the Huntington Beach oil field" (Gilluly and Grant, 1949, p. 526). A review of more recent leveling data by Estabrook (1962) indicates that between 1956 and 1961 the average annual subsidence over the Huntington Beach oil field was 0.14 foot; the cumulative subsidence over this interval was 0.70 foot (see figure 3).

Although records of subsidence at Huntington Beach during the early years of production (peak production was in 1923) are not available, Castle *et al.* (1969, figure

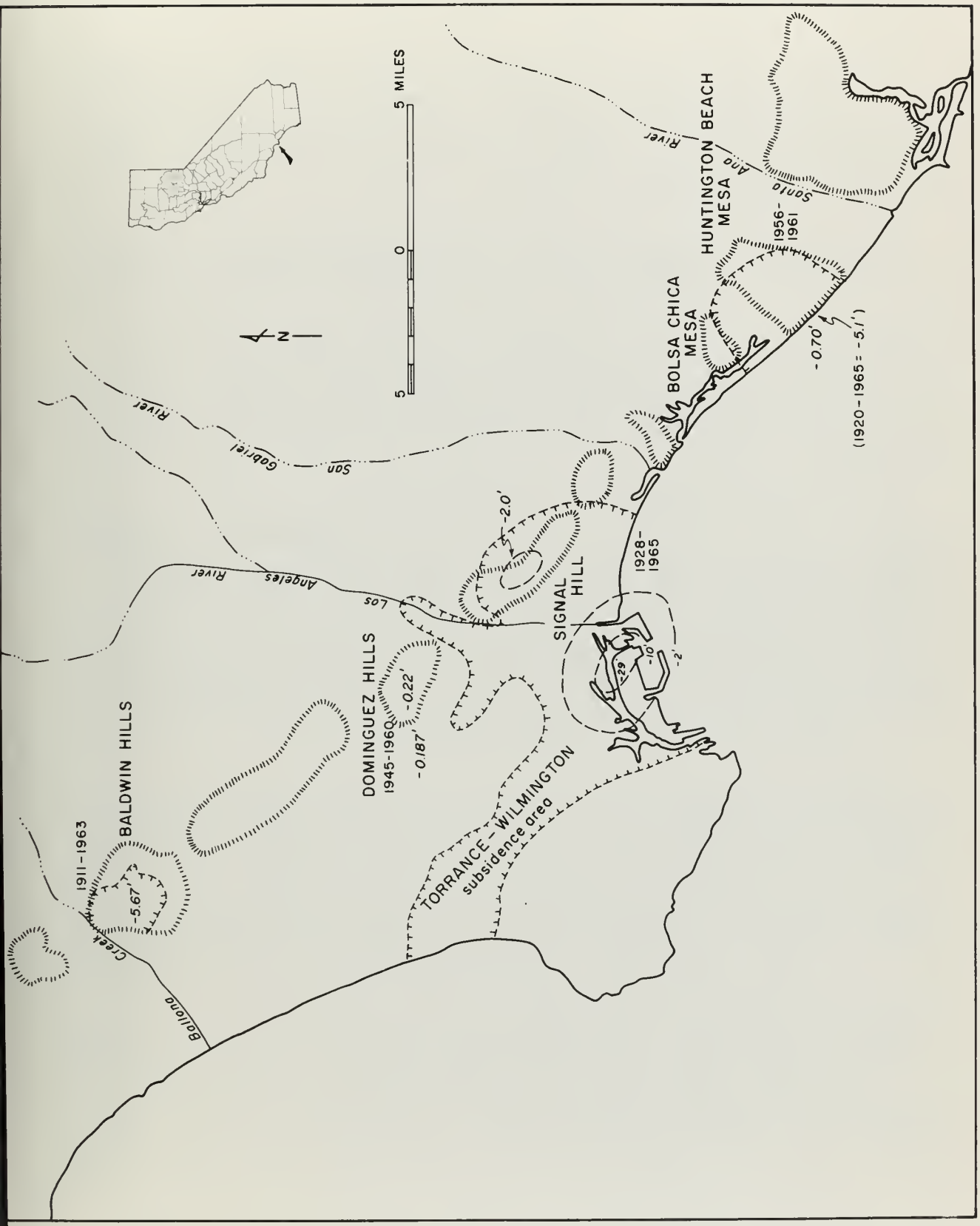

Figure 3. Differential subsidence along the Newport-Inglewood structural zone and Torrance-Wilmington area.

6) have estimated the subsidence for the interval 1920 to 1933 and combined that figure with the measured subsidence from 1933 to 1965. Total maximum cumulative subsidence near the center of subsidence has been estimated at 5.1 feet.

Elevation changes over most other portions of the Newport-Inglewood structural zone have been either insignificant or so slight that they have not been reported in the literature. "Measured surface subsidence has been slight over the Dominguez field and almost unmeasurable over the Rosecrans field" (Castle and Yerkes, 1969, p. 130). Two points, indicating stations which have subsided within the boundaries of the Dominguez oil field, are shown in figure 3.

The actual or potential surface effects of differential subsidence must be viewed as a geologic hazard. A reduction in elevation of the land surface can cause problems most easily seen in areas that are at or slightly above sea level. With continued subsidence, that portion of the Newport-Inglewood zone lying along the coastal section of Orange County may be subject to flooding and increased exposure to wave damage, especially at times of high tide or during storms. Nearby Wilmington provides an example of the costly effects of subsidence at a tidewater locality (Mayuga, 1965). Furthermore, slight local changes in elevation in areas of low relief can have a large effect upon gradients causing problems for drainage channel and sewer construction and maintenance.

Horizontal surface movements that accompany differential subsidence can create additional problems. The effects resulting from horizontal displacement range from damage to structures through misalignment of supports or piles to the rupturing or kinking of pipelines. Documentation of horizontal movements requires reobservation of precise triangulation networks. Because of this, horizontal movements related to subsidence along the Newport-Inglewood structural zone have been documented only for the Baldwin Hills (Alexander, 1962). "The horizontal displacements are directed generally toward the center of subsidence and almost precisely perpendicular to the isobases of equal elevation change; maximum measured movement between 1934 and 1961 is reported as 2.21 feet" (Castle and Yerkes, 1968, p. 50).

Surface faulting associated with subsidence over oil fields has been recognized in several areas (Yerkes and Castle, 1969)--the only recognized faulting lying along the Newport zone is the Inglewood oil field in the Baldwin Hills. Surface manifestations of subsidence-related displacements in the Baldwin Hills are called "earthcracks" (California Department of Water Resources, 1964, p. 41). Although recognized as early as 1957, earthcracks did not receive much publicity until the intensive investigation into the causes of failure of the Baldwin Hills Reservoir on December 14, 1963. The report of the investigation (California Department of Water Resources, 1964) contains descriptions of 13 earthcracks and an aerial-photo map and several photographs showing their locations. Except for those in the bottom of the reservoir (called Fault I and Fault V), most of the earthcracks are located in the vicinity of the intersection of Stocker Street, Overhill Drive, and La Brea Avenue. Movement on the earthcracks was essentially dip-slip with the downthrown side of most toward the center of the subsidence bowl. The earthcracks "are concentrated along the eastern periphery of the subsidence bowl, approximately orthogonal to radii emanating from its center, and generally, parallel to pre-existing faults and joints" (Castle and Yerkes, 1968, p. 50). The vertical displacement across these earthcracks ranged from about 1 inch to 2 inches. Within the reservoir itself, since its completion in 1951, "a total maximum vertical displacement of about 7 inches has occurred on Fault I and about 3 inches on Fault V...as evidenced by the relative displacement of the asphalt seal underneath the reservoir" (Hudson and Scott, 1965, p. 168).

An alternative view on the development of earthcracks, to which the failure of the Baldwin Hills Reservoir is ascribed, was presented by Hamilton and Meehan (1971) who emphasized the spatial and temporal relationship of the earthcracks with the initiation and continuation of high-pressure fluid injection into oil-producing zones of the east block of the Inglewood oil field. They felt (p. 344) that they had established that "the earth-crack ground rupturing of the Baldwin Hills was genetically related to high-pressure injection of fluid into the previously faulted and subsidence-stressed subsurface." They mentioned, however, that the opening of the crack which ultimately caused the failure of the reservoir was observed as early as 1952, five years before the full-scale waterflood program began. Accordingly, they stated (p. 339) that "this stage may therefore represent ground movement attributable to differential subsidence with little or no effect of pressure injection." It would appear that, because the surface cracking began before injection was started, it is still uncertain as to how much influence injection had on the development of earthcracks.

Earthquake-associated subsurface displacements on faults in the Inglewood oil field, revealed by damage to oil wells, are discussed on in the section on the October 1941 quake. Castle and Yerkes (1969, p. 121) suggested that the oil well damage "is consistent with faulting along the subsurface projection(s) of one or more of the earth cracks." Furthermore, "because production from the Inglewood field has been overwhelmingly from the Vickers zone, the apparent restriction of damage or inferred rupturing to producing zones no deeper than the Vickers suggests that the subsurface faulting and surface cracking are thus related to the exploitation of the field" (Castle and Yerkes, 1969, p. 121).

Subsurface faulting associated with earthquakes revealed by damaged oil wells in the Rosecrans and Dominguez oil fields is discussed in detail on pages 94 to 95 . Subsidence over these fields is slight (Castle and Yerkes, 1969, figure 51). The relation between subsurface displacements and subsidence is unknown. However, by analogy with the subsidence-related subsurface effects at Inglewood and the more extreme effects at Wilmington (see Richter, 1958, p. 155-156), it is possible that the displacements at shallow depth on faults in the Rosecrans and Dominguez fields resulted from near-surface readjustments related to the withdrawal of fluids.

The costly damage resulting from subsidence in the Wilmington area made it obvious that steps had to be taken to stop or, at least, decelerate the rate of subsidence. It was decided by the agencies involved and the oil producers that this could be brought about through a program of repressuring the oil reservoirs by water injection. Water injection is very expensive and was made economically feasible at Wilmington only because of the secondary recovery of oil which accompanies the injection. Water injection has been successful in greatly reducing the subsidence rate, although it has not succeeded in stopping it altogether (Mayuga and Allen, 1966, p. 285).

The rate of subsidence of benchmarks overlying the Inglewood oil field decelerated after water flooding began in the Inglewood field in 1954 to stimulate secondary recovery of oil (California Department of Water Resources, 1964, plate 9). Although the injection of water into strata from which fluids have been withdrawn is done primarily to increase recovery of oil, it has been successful in combating subsidence. However, excessive or unmonitored injection itself poses a significant problem--that of induced earthquakes. According to Hamilton *et al.* (1969, p. 66):

> Fluid injection seems to have caused earthquakes in at least two places. The injection of water into a 12,000-foot-deep well at the Rocky Mountain Arsenal northeast of Denver, Colo., is generally considered to have initiated the earthquake sequence that began there in 1962 (Healy and others, 1968). Three of these earthquakes had magnitudes greater than 5 and

> resulted in minor damage. The probable cause of the earthquakes was weakening of rock through increased pore pressure, which allowed natural rock stresses to be released. Another situation that possibly is similar to that in Denver was subsequently recognized in the oil field near Rangely, Colo. (Healy and others, 1968). The earthquakes there occurred in areas of high-pressure gradients generated by injection of water for purposes of secondary recovery.

It is possible that, as primary recovery of oil from Newport-Inglewood zone fields dwindles and secondary recovery becomes more widespread, the hazards due to continued subsidence will diminish; but this may be accompanied by an increase in the potential hazard of earthquakes induced by injection of water. In addition, as stressed by Hamilton and Meehan (1971), there is also the possibility of surface displacement, unaccompanied by earthquakes, along pre-existing faults where increased pore pressure from injection wells has reduced the shear strength along these fault planes.

Seismology

During the years immediately following the San Francisco earthquake of 1906, great interest in seismology naturally developed in California. One of the results of this interest was the formation of the Seismological Society of America. As a result of the conclusion that the San Francisco earthquake was caused by movement along a fault zone, several members of the Seismological Society attempted to devise a workable scheme of classification of earthquakes and their relation to known fault zones, especially large ones. One such attempt was made by H. O. Wood (1916). He attempted to relate most of the larger shocks from 1769 to 1916 to a few of the state's larger fault zones. A detailed account of this procedure appears in the section on earthquake history. The topic is mentioned here because in 1916 Wood did not know of the existence of the Newport-Inglewood structural zone and, therefore, proposed (p. 76) a hypothetical "San Pedro Submarine fault-zone" to account for the several large earthquakes that occurred in this portion of southern California (see page 61 herein) during historic time.

The first person to associate earthquakes with the Newport-Inglewood zone (although it was unnamed at the time) appears to be Homer Hamlin (1918, p. 23):

> All of you know of the low swell or ridge southwest of Los Angeles which extends from the Palms to Dominguez Hill, Signal Hill, and to the southeast of Long Beach. The surface formations exposed are all Pleistocene and in places contain mammalian remains similar to those found in the La Brea beds west of the city. The ridge is of recent origin, geologically, and the forces which have elevated it are apparently still operating.
>
> During 1917 no less than twenty earthquakes have been reported along this range of hills. In every case where the data have been worked up, the epicenter was found to be to the northeast of the hills in the low lands in the southwest part of the city. Evidently faulting or folding is in progress here, and more shocks may be expected. None of the shocks were hard, but those of February 13th and June 9th and 26th were strong enough to be noticed by many persons. No damage was done by any of them.

As far as can be determined from published works, Homer Hamlin was also first to suggest that there might be faulting and folding occurring along the Newport-Inglewood zone (see quotation above). Following the Inglewood earthquake of June 21, 1920, many geologists became interested in the Newport-Inglewood zone. The first geologist to have his comments published after the earthquake was Ralph Arnold who

had a "letter" printed in *Science* on August 6, 1920. In his short article, Arnold gave credit to Hamlin as being the first to recognize the seismic importance of the Newport-Inglewood zone. Arnold said (1920, p. 121):

> To the late Homer Hamlin more than anyone else is due the credit for identifying the connection between certain local structural lines and the earthquakes which have affected the region about Los Angeles, California, during the past month. Hamlin's work, to the writer's knowledge, covered a period of over fifteen years prior to his death a few weeks ago. He single handed, studied the cause of more than twenty earthquakes of varying degrees of intensity which have occurred in southern California during this period. Hamlin's conclusions, few of which unfortunately ever were put in print, were that the line of structural disturbance along which the epicentrums of most of the earthquakes were located, was that which extends from the Santa Monica Mountains, north of the Soldier's Home (about ten miles northwest of the business district of Los Angeles), in a southeasterly direction through the Baldwin Hills, Dominguez Hill, El Cerrito (near Long Beach), and thence easterly to the San Joaquin Hills northeast of Newport. The section along this line which has been the greatest offender is that extending several miles southeasterly from Baldwin Hills. From a study of the intensity records, Hamlin was inclined to believe that the actual epicentrums were coincident in general with a fault which paralleled the anticline forming the Baldwin and Dominguez Hills, and extending along the northeast base of these hills. This may be true, but the writer is inclined to the theory that the actual crustal movements which produced the shocks took place along the Baldwin Hills-Dominguez Hill line, and that the maximum surface reaction might have been greater to the east of the hills because of the unconsolidated character of the sediments in this direction.

Just as the great San Francisco earthquake of 1906 forced men to turn their attention to its cause and a study of its features (Lawson *et al.,* 1908), the Inglewood earthquake of 1920 focused the attention of geologists on the Newport-Inglewood structural zone. The only paper to deal in detail with the Inglewood earthquake and its destructive effects, its seismology (including duration, distribution of intensities, and aftershocks), and the geology of the region was that written by Stephen Taber (1920) under sponsorship of the Seismological Society of America. Included in his paper is a map (scale 16 miles to the inch) on which is depicted the "Inglewood-Newport-San Onofre fault." This map (see figure 4) is the first one to show a fault along the Newport-Inglewood trend, and Taber should be credited with naming the fault zone.

In 1923, Kew wrote an article discussing the Inglewood earthquake and the geology of the Baldwin Hills. Accompanying this article (see figure 5) is the first detailed map of some of the numerous faults in the vicinity of the Baldwin Hills. Kew (1923, p. 157) defined as the Inglewood fault that portion which crosses the Baldwin Hills. The Potrero fault (not then named) also appears on his map. Taber (1924, p. 199) protested Kew's designating as the Inglewood fault that short section which transects the Baldwin Hills and suggested that a portion of the Newport-Inglewood structural zone be called the Baldwin Hills fault and that the term "Inglewood" be reserved for the regional feature originally defined by him (1920).

In March 1923, the Seismological Society of America issued "A Fault Map of California" compiled by the president of the society, Bailey Willis, in cooperation with H. O. Wood. In the explanatory article which was intended to accompany or publicize the map, Willis (1923, p. 1) suggested that an equally appropriate title for the map would be an "Earthquake Map of California" because "the intimate connection existing between faults and earthquakes was clearly established by the researches carried out by the geologists who investigated the shock of April, 1906, that set fire to San Francisco..."

On the fault map, the first such effort of its kind, there are designated both "active" and "dead" faults. Willis (1923, p. 3) considered an active fault as "one on which slip is likely to occur." A different criterion was used for the faults of the southern part

of the state, which was compiled by H. O. Wood, who "designated as active all faults upon which there has been a movement within historic time, and also all faults upon which physiographic evidence of recent surface dislocation--'trace phenomena'--could be obtained" (Willis, 1923, p. 3).

Applying the above criteria to the Inglewood fault, Wood had no difficulty in defining the zone as an "active" one because "of the Inglewood earthquake of 1920 and it is presumably continuous with or intimately related to the fault zone that extends southeast past Signal Hill and Huntington Beach, defining the coast to San Diego and beyond" (Willis, 1923, p. 11). The portion of this statement dealing with the extension of the fault zone to the south is conjecture. The idea that the Newport-Inglewood structural zone defined the southern California coastline appears to have been around for a few years previous to the compilation of the "Fault Map" (see figure 4). In spite of such

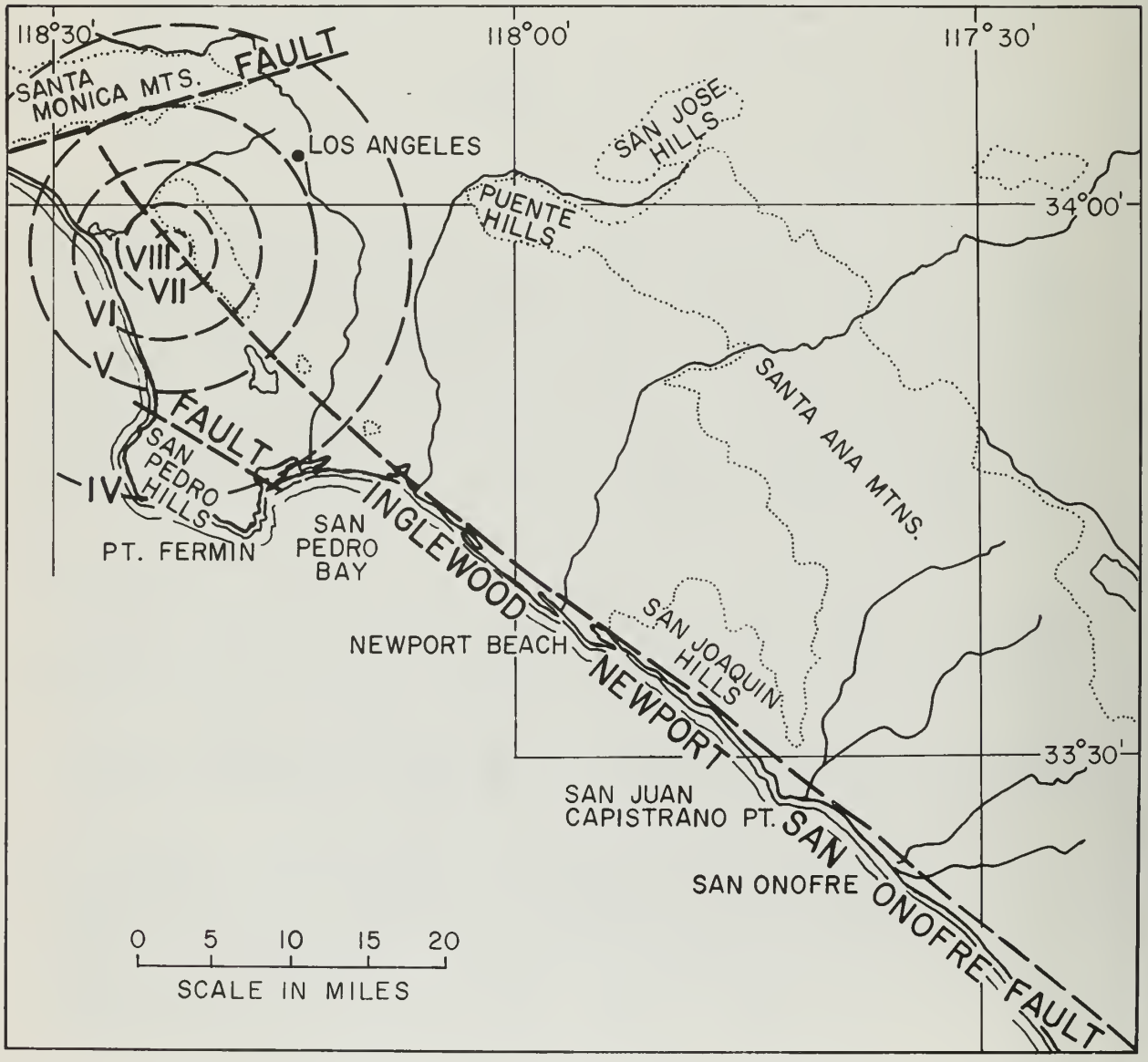

Figure 4. The "Inglewood-Newport-San Onofre fault" as mapped by Taber (1920, Seismological Society of America Bulletin, v. 10, p. 134). This map, which has been simplified and redrawn for clarity, is the first published map to depict a fault along the Newport-Inglewood trend. Map also shows isoseismal lines (Rossi-Forel intensities) for the June 21, 1920, Inglewood earthquake.

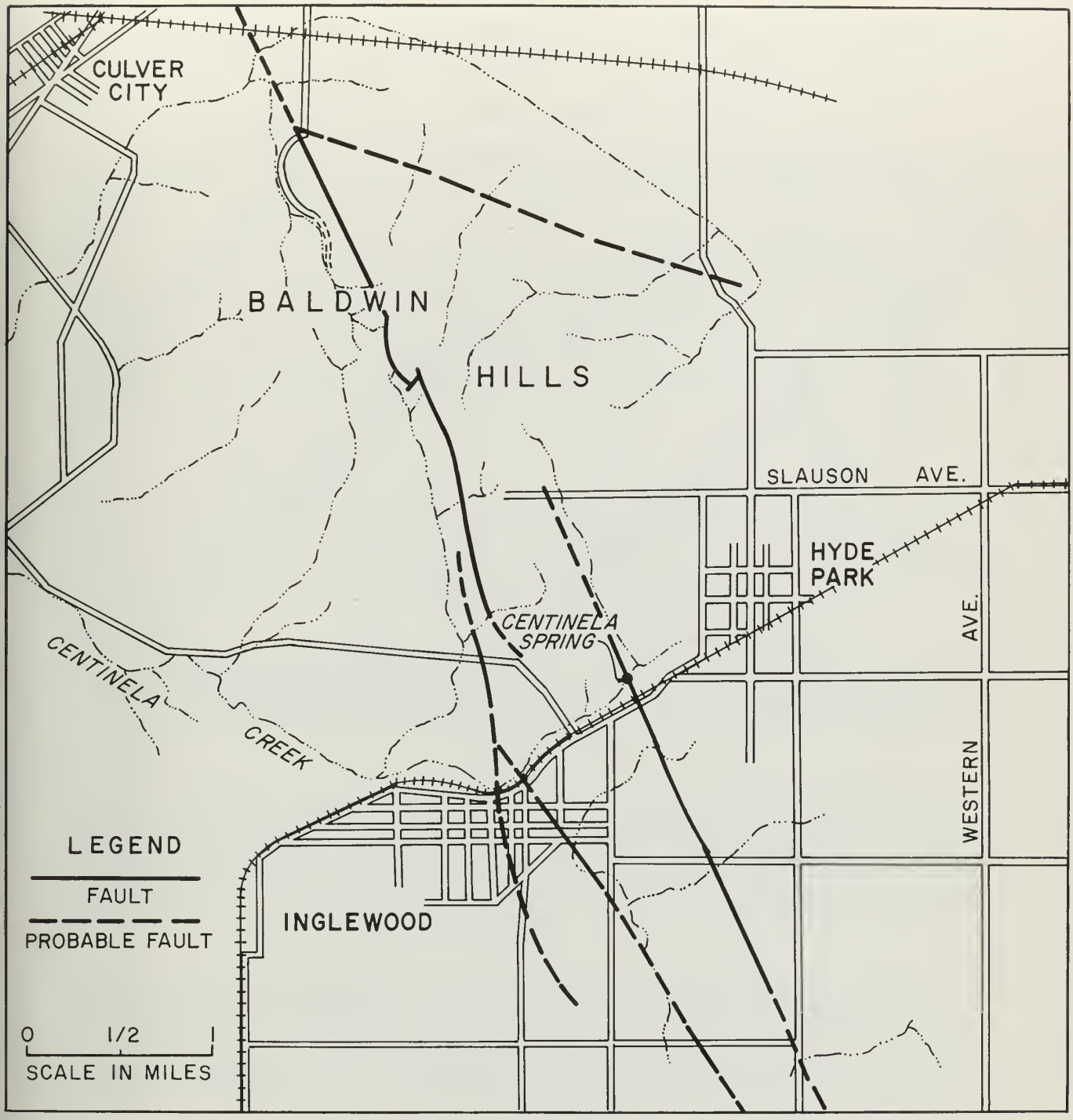

Figure 5. Sketch map of the Baldwin Hills showing location of the Inglewood fault. (From Kew, 1923, Seismological Society of America Bulletin, v. 13, pl. 26).

confidence in the location (not to say existence) of the southern extension of the zone, Willis indicated in a subsequent article that he had no idea just how far and where the supposed southern portion extended. This can easily be seen in plates 8, 9, and 12 that accompany Willis' 1923-24 article entitled "Earthquake Risk in California." On each of these maps, the "San Diego-Inglewood fault-zone" is shown occupying a different position. In the article, Willis stated (1924, p. 23) that the "Inglewood fault runs from

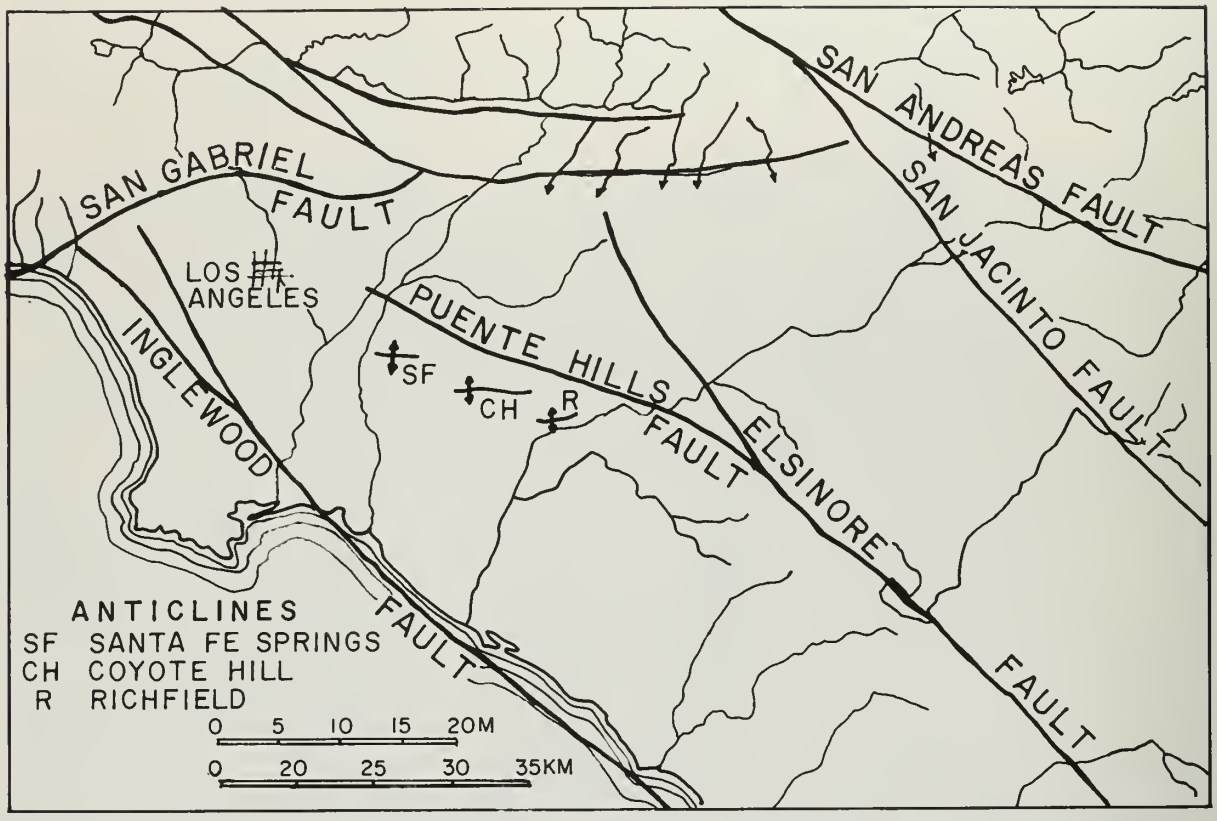

Figure 6. Bifurcating Inglewood fault as depicted by Willis, 1923-24, Seismological Society of America Bulletin, v. 14, pl. 4. Note also that the Santa Monica fault of current terminology is called the San Gabriel fault and the current Whittier fault is called Puente Hills fault.

near Los Angeles down the coast to San Luis Rey, leaving San Diego a few miles southwest of its course; and close to San Diego and through La Jolla is a parallel fault extending northwesterly under the sea and passing probably near San Pedro in the latitude of Los Angeles." This speculation appears to be the second place such a fault system was suggested. Earlier, Taber (1920, p. 141) discussed the evidence he used as his basis for plotting the fault beyond Newport. More is written about such a configuration in the section on alternative structural hypotheses (see page 51).

Also accompanying the Willis (1923-24) article is a larger scale map of the Los Angeles region (v. 14, plate 4). This map is reproduced here (figure 6) because it shows the same bifurcation of the Newport-Inglewood zone that appears on the "Fault Map of California." This particular configuration of the zone in the Los Angeles basin appears to be unique to the maps of Willis (actually H. O. Wood) and those which are probably based upon it.

Scores of publications dealing with earthquakes and the seismicity of the zone are listed in Appendices A and B. Seismic phenomena and earthquake-related features are discussed at length in the section on the earthquake history of the zone. References, both published and unpublished, dealing with subsidence and other phenomena along the zone, as well as site investigations for proposed structures, are cited in the appropriate places within the text and also are listed in the bibliography.

HISTORY OF HYPOTHESES ON THE ORIGIN AND DEVELOPMENT OF STRUCTURAL FEATURES

As a direct result of the rapid development of oil fields along the Newport-Inglewood zone in the 1920s, a large amount of subsurface data became available. Discussions of the over-all structure of the zone soon appeared. However, the first papers in which the structure of the zone was discussed were stimulated by the 1920 Inglewood earthquake (Taber, 1920, Kew, 1923). In much the same way that the shape of a foundation determines the configuration of a structure built upon it, the published reports following the Inglewood earthquake and their accompanying maps of a regional "Inglewood fault zone" probably served to constrain future workers to base their conclusions on a "known and mapped" feature. Petroleum geologists expanded upon the concept of the Newport-Inglewood "fault" as a regional feature in order to explain the arrangement and tectonic history of the oil fields along the Newport-Inglewood structural zone.

Evidently, Eaton (1923 and 1924) was the first to hypothesize that lateral movement along a regional fault zone was responsible for the formation of the series of *en echelon* anticlinal structures that give surface expression to the Newport-Inglewood structural zone. Closely following the papers by Eaton was a paper by Ferguson and Willis (1924) in which they hypothesized that (p. 579):

> ...underlying the 10,000 or 15,000 feet of sediments in the Los Angeles Basin is a more or less rigid basement in which movement manifests itself in shearing rather than in folding, and that movements along shear zones in this buried basement have produced folding, sagging, or faulting in the overlying sediments according to the direction and amount of movement.

The trace of the "Newport-Inglewood fault" on their map (figure 7) closely resembles the forked appearance of the trace of the "active" portion of the Newport-Inglewood zone as shown on Bailey Willis' 1922 "Fault Map of California" (compare figure 6 and figure 7).

The tectonic map accompanying the summary of the geology of the Los Angeles basin written by Vickery in 1928 is perhaps the most detailed produced to that time. This map was compiled by W.S.W. Kew and modified by Vickery and is reproduced here (figure 8) as an indication of the state of the knowledge of the structures along the Newport-Inglewood zone at that time. Notice that the "forked" fault system of Willis (1923) and Ferguson and Willis (1924) is not shown.

Early summaries of the tectonic history of the zone are characterized by generalizations about the cause and effect relationship between an inferred deep-seated shear zone and the surface features (folds and faults as delineated by oil field development). This situation continued into the 1930s when a detailed analysis of the theories of origin of the structures along the Newport-Inglewood zone was presented by Reed and Hollister (1936, p. 1671-1679). Reed and Hollister (1936) pointed out that, although oil wells drilled in the vicinity of Seal Beach and Long Beach and surface observations at Baldwin Hills offer proof that the topographic scarps at these places represent the traces of faults, there is uncertainty about the existence of a deep-seated

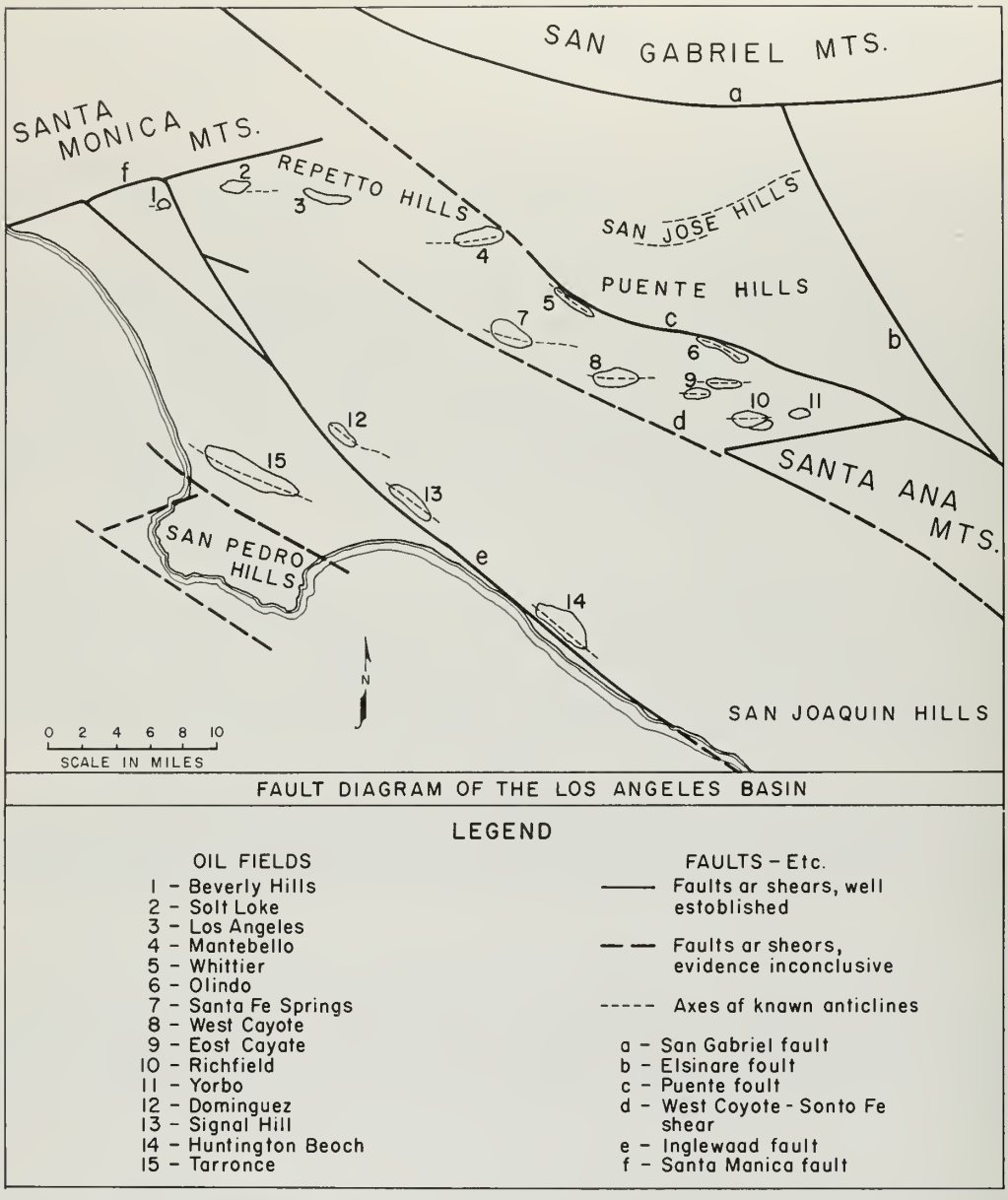

Figure 7. Fault map (redrawn) from Ferguson and Willis, 1924, American Association of Petroleum Geologists Bulletin, v. 8, p. 578.

Newport-Inglewood fault. They asked (p. 1675), "But where, exactly, is the Inglewood fault of popular conversation?", and concluded that "in spite of the frequency with which this fault has been mentioned and even shown on published maps [see figures 4 through 8] its existence remains a hypothesis." Recognizing the necessity to emphasize the difference between the known near-surface *en echelon* faults and the hypothetical major basement shear zone they stated (p. 1675):

> The oblique Baldwin Hills [now called Inglewood] fault is probably no more than a prominent member of the *en echelon* series...and the supposed course of the fault farther south--and farther to the north, for that matter--is in the opinion of the writers scarcely entitled to rank even as a good hypothesis.

Even though they lacked the wealth of data revealed by the subsequent drilling of numerous very deep wells, Reed and Hollister (1936) listed several lines of evidence that support the hypothesis of earlier workers; that the aligned surface features are related to a major basement fault zone. They discussed the mechanical considerations in the development of *en echelon* fractures and concluded (p. 1676) that the "Newport-Inglewood fault, *if it exists* [italics supplied], should lie not athwart the uplift or along its margin, but under its axial part." They adduced the significance of the San Onofre Breccia of early middle Miocene age to lie "in the suggestion it gives that the southeastern continuation of the Newport-Inglewood structural belt has been a locus of important movements since Middle Miocene" time (p. 1677). Furthermore, they pointed out that "the belt is structurally active and important" (p. 1675) as indicated by the 1920 Inglewood and 1933 Long Beach earthquakes.

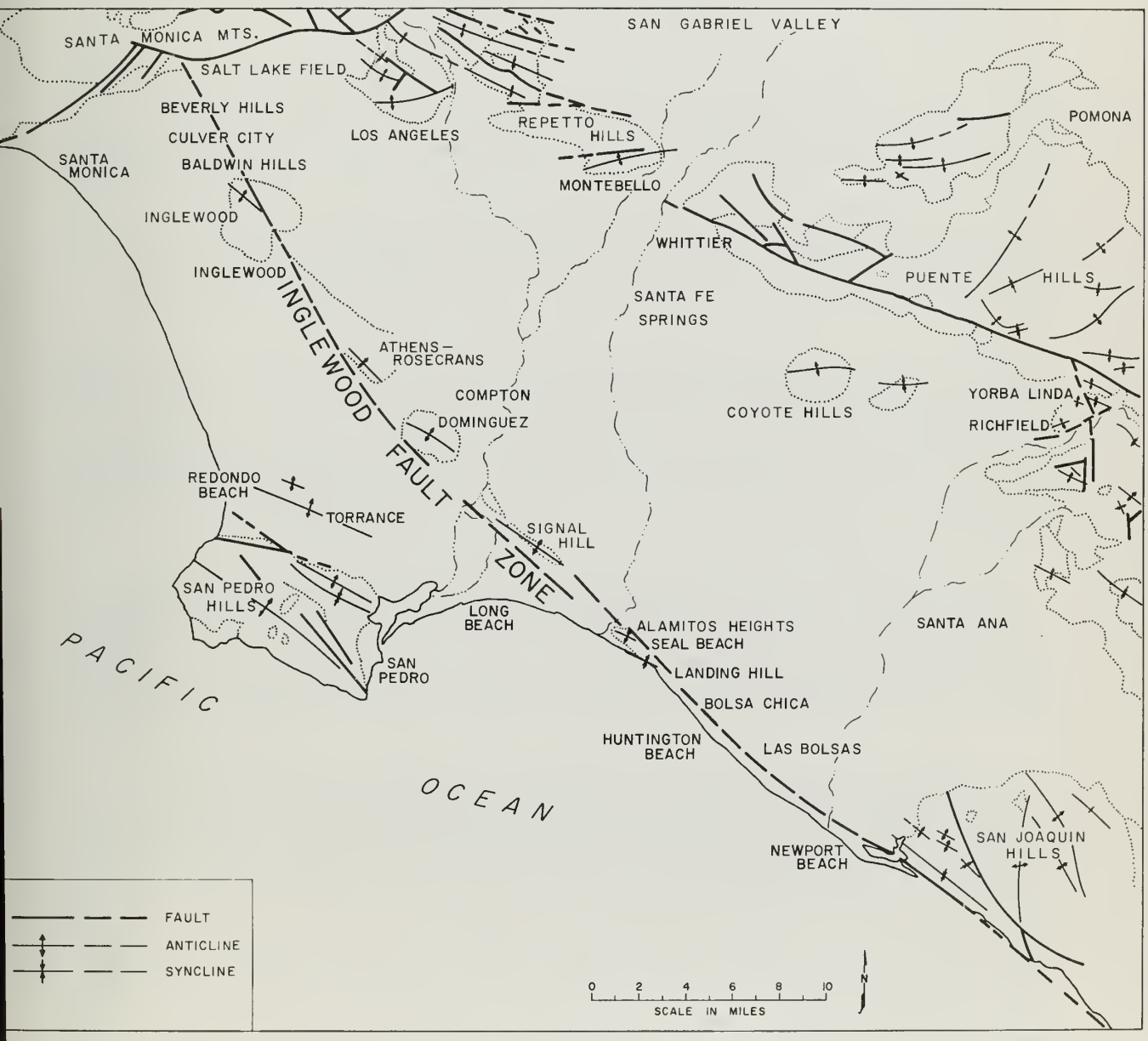

Figure 8. A portion of an outline map of the Los Angeles basin by W.S.W.Kew and modified by F. P. Vickery (1928, p. 357) redrawn for clarity.

In summary, Reed and Hollister (1936, p. 1679) concluded:

> ...it may be said that in the blanket of Upper Miocene and later strata the Newport-Inglewood structure is a domed, slightly faulted anticline; at a depth of several thousand feet it may be a granite-Franciscan contact that has been a locus of movement since the Middle Miocene and perhaps much longer. The more recent disturbances may have involved a slight shearing tendency which puckered the strata into small domes and fractured them with minor *en echelon* faults.

In his excellent review of the stratigraphy of the Los Angeles basin oil fields, Wissler (1943, p. 227) held a very similar view:

> The fields of the Inglewood-Newport uplift consist of a series of faulted domes *en echelon* arrangement along the deep-seated Inglewood-Newport fault zone; a fault zone which may well represent the line of demarcation between the metamorphic basement rock on the west and the granitic basement rock on the east.

White (1946, p. 10) also suggested, in his review of data from wells to basement on the western side of the zone, that the Newport-Inglewood "fault-rift marks the eastern boundary of the schist formation." The above quotations, along with statements in more recent papers , show that, although subsurface data became increasingly available due to the extensive drilling for oil in the vicinity of the Newport-Inglewood trend, most structural hypotheses formulated subsequent to that of Reed and Hollister do not differ significantly from their with regard to the post-middle Miocene activity along the Newport-Inglewood structural zone.

The tabulation and discussion of data from wells to basement presented by Schoellhamer and Woodford (1951) provides the best summary of this material. Their map depicts the configuration of the Catalina Schist basement surface in a generalized way by means of structure contours. The information from wells concerning depths to basement rock in oil fields along the Newport-Inglewood trend was not abundant enough to allow delineation of the shape of the pre-Miocene basement surface. Schists were, in fact, encountered only in the Long Beach and Dominguez oil fields.

At Signal Hill, basement rocks similar to Catalina Schist are present at depths of 14,700 feet on the southwest or downthrown side of the Cherry-Hill fault and 10,830 feet on the northeast or upthrown side of the fault. These penetrations to the schist were made in Shell Oil Company wells. According to Schoellhamer and Woodford (1951):

> The Shell Oil Co.'s deep drilling in the Long Beach (Signal Hill) field in the years 1944 to 1948 revealed a basement wedge in the anticlinal core, probably bounded by faults of the Newport-Inglewood zone... These two wells establish the presence of the Catalina schist northeast of one of the major faults along the Newport-Inglewood fault zone. The northeastward extension of this schist surface is unknown. Perhaps its northeastern boundary is another fault of the Inglewood zone.

A comparison of Schoellhamer and Woodford's Section H-I-J (1951, Sheet 1) with Section E-F (plate 4) of Yerkes *et al.* (1965) shows that Schoellhamer and Woodford's supposition was correct. The Texaco, Inc., well Bixby (NCT-1) 2 encountered schist just below a depth of 12,000 feet northeast of the Shell Oil Company wells, proving that a horst does, indeed, underlie the Long Beach oil field.

During the 1950s, several more papers dealing with the geology of the Los Angeles basin and southern California were published. Several significant papers appeared in Bulletin 170 of the California Division of Mines (1954). Two papers in particular discuss the Newport-Inglewood structural zone. Woodford *et al.* (1954, p. 74) reiterated that the Newport-Inglewood zone probably marks the boundary "between basement rocks of different composition and different facies" but that "there is also considerable doubt... about the amount and direction of the net total displacements." Furthermore, they commented (1954, p. 77) that "along the Newport-Inglewood zone, folding is more prominent than faulting. The late Tertiary and Quaternary faulting cannot be ignored, however, and some right-lateral strike slip is said to have been demonstrated by subsurface studies."

The other paper in Bulletin 170 referring to the Newport-Inglewood zone is by Mason Hill (1954). He stated (p. 10) that the Newport-Inglewood zone "is overlain by east-southeastward-trending en-echelon folds, and electric-log correlations demonstrate a few miles of right lateral-slip." It should be pointed out, as discussed on page 11 and table 1, that evidence from various oil fields indicates that the amount of displacement apparently varies from field to field in an irregular manner for various faults along the zone. In addition, as was aptly stated by Wissler (1943, p. 230), the lithologic variation within upper Miocene and lower Pliocene strata from field to field is considerable. Speaking of the Repetto (lower Pliocene) units in the different fields, Wissler stated:

> Some intervals which are predominantly shale in one field, become so interbedded with sand in others as to be lithologically entirely unrecognizable; at the same time sandy intervals may become shale bodies, much to the chagrin of the one who attempts to correlate solely by means of electric logs.

Furthermore, Wissler (1943, p. 230) gave an example of an error of 1,500 feet in correlation by electric logs that was revealed by paleontological data.

Wissler noted and gave several examples of the variation in thickness of the strata between different fault blocks in most of the oil fields along the zone. He also pointed out (1943, p. 230) that:

> These rather abrupt changes in thickness on opposite sides of the faults are frequently accompanied by appreciable differences in abundance and state of preservation of the microfauna. In such instances the lithology and thickness as well as the abundance and state of preservation of the foraminiferal assemblage on one side of a fault may closely match that of a relatively distant location on the opposite side. Therefore the author is of the opinion that, while some of these differences in thickness may be due to progressive movement contemporaneous with deposition, many of them are due to differential horizontal movement which has brought sections of different thicknesses and microfaunal character into juxtaposition.

The suggestion that large displacements have occurred along the San Andreas and other California strike-slip faults was made by numerous workers in the 1950s (for example, Hill and Dibblee, 1953); and, as the concept became popular, it was utilized more and more to explain the tectonics of many areas in California. In 1954, Willis attempted to apply a geometrical analysis to structures in the Dominguez, Potrero, and Inglewood oil fields in order to demonstrate that there is some validity to the hypothesis that horizontal movement along a basement fault was responsible for formation of the structures of the zone. Willis (1954, p. 60) concluded from his review of the literature that "The literature in general supports the hypothesis that the structure of the uplift originated from horizontal movements along a deep-seated fault." The desire to explain the observed *en echelon* arrangement of the oil fields along the zone

resulted in an appeal to a simple model of two basement blocks moving past each other. For instance, Ferguson and Willis (1924, p. 579) suggested, after making an analogy between western Los Angeles basin geology and two pieces of cardboard moving underneath tissue paper pasted to them, that "the motion on the northwesterly trending faults of the basin is probably similar to that of the cardboards, or largely lateral and to the northwest on the ocean side." This concept, also discussed by Reed and Hollister (1936), did not change in popularity in the thirty or so years since it was first proposed by Eaton (1923; 1924). It is likely that many workers readily adopted this explanation without critically appraising it, thereby resulting in the apparent and almost unanimous acceptance of the idea. That things are not so simple, structurally, along the zone was brought out by Woodford *et al.* (1954, p. 77) who said:

> The discovery of deformed basement cores in the anticlines along the Newport-Inglewood zone seems to require a somewhat different mechanism, but one whose actuation is not immediately apparent.

An example of ready acceptance of the lateral-slip hypothesis for the development of structures along the Newport-Inglewood zone appears in a paper by Moody and Hill (1956). Although they recognized that the faults in the various oil fields are not segments of a continuous fracture zone, they believed that the orientation of the *en echelon* folds associated with the Newport-Inglewood structural zone developed as a result of "recent right lateral movement" (p. 1218-1219). They stated:

> Detailed subsurface work in the oil fields of this trend does not reveal a single clear-cut fault trace, but many parallel faults are recorded in a narrow zone. The authors believe that these multiple fractures are shallow manifestations of a single right lateral wrench fault at depth that is part of the San Andreas system. The many oil fields along this trend are located on drag folds developed by right lateral motion.

Although evidence for a certain amount of right-lateral displacement in some of the fields is good for the older rocks, the over-all style of the more recent movements is still ambiguous. Castle and Yerkes (1969, p. 7) determined that 3,000 to 4,000 feet of right-lateral displacement has occurred since middle or late Pliocene time as recorded by the offset structural crest on the top of the "Gyroidina" zone in the Inglewood oil field. They also suggested (p. 7) that the apparent topographic offset along the Inglewood fault in the Baldwin Hills totals between 1,500 and 2,000 feet, in a right-lateral sense.

Much of the confusion in interpreting the complexity of the structure along the Newport-Inglewood zone is a result of the failing of earlier workers to provide detailed data or discussions explaining that "the many parallel faults" in the various oil fields demonstrate different directions, magnitudes, and histories of displacement (see table 1 and the discussion on page 11). These observations were recently reiterated by Harding (1973), who also attributed the pattern of the Newport-Inglewood structural zone to "wrenching" (strike-slip faulting). He presented "a more comprehensive and detailed synthesis of the younger Neogene subsurface structuring of the zone, both in regional pattern and in local detail" (p. 3) so that he could cite the zone as a natural example of a "small-displacement wrench zone" to which analogies could be drawn from experimentally produced similar structural patterns in model studies.

McCulloh (1957) pointed out that knowledge of the subsurface geology, outside of areas explored by the drill, can best be gained by geophysical methods, especially the determination of the presence and trend of gravity anomalies. McCulloh (1957)

prepared a Bouguer gravity map of the western portion of the Los Angeles basin accompanied by a discussion. He noted that:

> Wherever major folds occur in the Tertiary sedimentary rocks of the Los Angeles basin, the pre-Upper Cretaceous basement rocks have been deformed in the same degree beneath the sedimentary cover.

He gave several examples of this observation, one of which was the Dominguez-Lawndale-El Segundo anticlinal trend, revealed by the shallow depth to the basement surface in these oil fields. Furthermore, McCulloh (1957) noted that the Bouguer gravity values "rise steadily and rather steeply across the Newport-Inglewood fault zone."

McCulloh (1957) also pointed out that the gravity data do not clarify the relationship between the Newport-Inglewood and the Santa Monica fault zones. In 1958, Barbat (p. 43) summarized what probably represents a concensus of the view held by petroleum geologists with respect to the trends of the Santa Monica fault zone and Newport-Inglwood structural zone:

> What had been strike-slip movement in a left-lateral sense in mid-Miocene shifted to dip slip movement by mid-Pleistocene time. The Santa Monica-San Gabriel Mountain System was thrust up relative to the area to the south. The Newport-Inglewood fault system, which probably played some role of importance in the mid-Miocene separation of positive (schist surface) and negative (thick pre-basinal strata) areas progressively assumed right-lateral slip. The basic failure pattern suggested is taken as evidence of a counterclockwise rotation of the direction of principal stress.

More recently, Yerkes and Wentworth (1964, p. 17) developed a hypothesis with regard to the Malibu Coast fault (part of the Santa Monica fault system) and the Newport-Inglewood zone:

> The Malibu Coast and Newport-Inglewood zones are evidently underlain by crustal-block faults that juxtapose Catalina Schist basement of the Continental Borderland on the south and west against granitic and metamorphic basement of the Transverse and Peninsular Ranges on the north and east. The Newport-Inglewood zone exhibits right-lateral strike slip in the overlying sedimentary section and the Malibu Coast zone exhibits strong evidence of north-over-south thrusting. These two zones are considered to be related parts of a primary crustal fault system, on which rocks of the Continental Borderland have been moved relatively northward along the Newport-Inglewood zone, and beneath rocks of the Santa Monica Mountains along the Malibu Coast zone at their overriding south margin.

In supporting the statement that the Newport-Inglewood zone represents the eastern boundary of the continental borderland, they cited Woodford *et al.* (1954), Barbat (1958), and Woodford (1960). A generalized restatement on the above position appears in Yerkes *et al.* (1965, p. A48):

> Throughout its course the fault zone at depth is evidently the boundary between western basement on the southwest and eastern basement on the northeast... North of the Inglewood oil field the basement boundary merges with or is terminated by the Santa Monica fault zone; south of the Inglewood oil field the boundary probably parallels the surface trace of the zone, but, on the basis of gravity data, it is about 1.5 miles to the northeast...

In the past few years, intensive studies of the structural and deformational history of the Newport-Inglewood structural zone have been made as a necessary part of the investigation of sites for the construction of nuclear-powered facilities (for example, Yerkes and Wentworth, 1964; 1965; and Castle, 1966; Jahns *et al.*, 1971). An exhaustive summary and review of the best information available on the various aspects of the Newport-Inglewood structural zone were made by Castle (1966) who considered

the following aspects of the zone: (1) extent of the zone, (2) topographic expression, (3) the hypothetical boundary fault or "major crustal fault," (4) the interpretation of the *en echelon* fold-fault pattern and evidence for lateral displacement and vertical displacement, (5) the width of the zone of deformation, and (6) the history of deformation with special emphasis on evidence for post-Pleistocene tectonic activity (warping and folding, faulting, and seismicity along the zone). Additional information, made available since Castle's summary, especially southeast of Newport Beach and further speculations about several of these points, appear in the section entitled "Inferred History of Deformation".

During the past decade, the concepts of sea-floor spreading (Dietz, 1962; Hess, 1962) and the new global tectonics (Isacks *et al.,* 1968; Heirtzler *et al.,* 1968) have stimulated discussions and reappraisals of the tectonic framework of many areas, particularly California. Making use of the concepts of plate tectonics and the underthrusting of the Pacific Ocean floor beneath southern California, Yeats (1968a; 1968b) has written controversial papers which depart from more traditional views. Yeats, who explicitly assumed the Catalina and Pelona schists to be correlative, did not consider the Newport-Inglewood zone to be the boundary between eastern (crystalline) and western (schistose) basement rock types but interpreted the floor of the entire Los Angeles basin to be composed of Catalina Schist (1968a, p. 316). He admitted that this is not a new idea. Schoellhamer and Woodford (1951) suggested that some difficult-to-interpret rocks encountered in deep wells in the Brea-Olinda oil field along the Whittier fault might represent specimens of Pelona Schist and, furthermore, that schists could conceivably underlie the whole Los Angeles basin. With the information later made available, these workers now believe otherwise: "Eight wells drilled in the Brea-Olinda oil field near the south west margin of the northeastern block bottom in foliated metavolcanic rocks tentatively correlated with the Santiago Peak Volcanics of the eastern basement complex" (Yerkes *et al.,* 1965, p. A24; also see Woodford, 1960, p. 407).

Yeats, however, (1968a, p. 317) preferred to consider the Brea-Olinda oil field basement rocks and certain basement rocks beneath the Las Cienagas oil field to be "Pelona-like." Yeats proposed that the Los Angeles basin is a Miocene rift and that blocks of the crystalline basement "moved independently of one another as rootless, iceberg-like rafts floating on a sea of Franciscan" (1968b, p. 1698). The validity of this hypothesis rests heavily on the assumed correlation of Franciscan, Catalina, and Pelona rocks. If the Newport-Inglewood zone does indeed represent the surface expression of the buried boundary between unlike basement-rock types, the hypothesis will no longer be tenable.

Mason Hill (1971) holds a traditional view on the post-middle Miocene development of the Newport-Inglewood structural zone relating it to a "Pliocene-Holocene strain system of north-south shortening" (p. 2960). Recently, Hill (1971) also has made use of the concepts of plate tectonics in defining the "Southern California subduction zone" to have been the locus of "great east-west shortening (2,000 mi)" during Mesozoic time when what is now overlain in part by the Newport-Inglewood trend is inferred to have been a major thrust zone between "oceanic and continental basement rocks facies." His purpose for making the distinction between the present-day Newport-Inglewood zone of *en chelon* folds and faults and the Mesozoic southern California subduction zone was to emphasize the great difference between the orientations of the tectonic forces and the scale of the deformations involved.

INFERRED HISTORY OF DEFORMATION

The pre-middle Miocene history of the Newport-Inglewood structural zone is enigmatic and leads, naturally, to speculation about the nature and style of the deformational processes involved in the development of the structure upon which middle Miocene and younger rocks were deposited.

Certain limiting conditions on the timing and the sequence of events during the early history of the zone have been summarized by Yerkes *et al.* (1965, p. A16):

> Because detritus from the distinctive western basement rocks is absent in strata older than middle Miocene, because the western basement is unconformably overlain by middle Miocene strata, and because these basement rocks are not known to be intruded by Upper Cretaceous plutonic rocks, it is inferred that the eastern and western basement complexes were juxtaposed along the Newport-Inglewood zone by large-scale movement during some interval between early Late Cretaceous and early middle Miocene time.

In addition to not knowing the exact time of the "juxtaposition" of the basement complexes, we also do not know what type of "large scale" movement was involved. This aspect of the early history of the zone has led to much speculation, stimulated in recent years by the concepts of plate tectonics. Among the several different styles of faulting that could have been involved in the rearrangement of the basement complexes, three types are discussed in the following paragraphs: high-angle reverse faulting; large-scale westward overthrusting of the eastern crystalline rocks over the western schistose rocks or, conversely, underthrusting of the western rocks beneath the eastern ones; or strike-slip faulting accompanied by large lateral displacement.

Although high-angle reverse faulting of unlike basement terranes may have taken place, this type of faulting ultimately requires an explanation for the unlike rocks to be associated, even if it places the initial contact at great depth on the east.

That the two unlike basement terranes were brought together as a result of overthrusting or underthrusting is considered more probable than for the rearrangement to have been caused by lateral-slip faulting. The speculative argument in favor of major thrust faulting and against transverse faulting is based upon an analogy with the dominant deformational style inferred to have occurred during late Mesozoic time elsewhere in California (Irwin, 1964; Davis, 1968; Dickinson and Grantz, 1968, p. 290).

Recently, Hill (1971) and Jahns *et al.* (1971) utilizing concepts of plate tectonics deduced that the two unlike basement types were brought together as a result of thrust faulting in response to east-west crustal shortening. In their view, the Newport-Inglewood zone of today coincides with the "Southern California subduction zone" of Mesozoic time. As postulated by Hill (1971, p. 2959), the origin of the southern California subduction zone

> ...according to the hypothesis of plate tectonics, results from the Farallon and Pacific plates plunging under the American plate, perhaps to compensate for sea-floor spreading from the mid-Atlantic Ridge. ... The period of subduction seems to have ended before Late Cretaceous time because Upper Cretaceous strata are inferred to overlie the oceanic-continental basement contact, and by analogy, to overlie a similar basement rock contact marked by the Sur-Nacimiento zone in the central Coast Ranges...

Furthermore, Hill (1971, p. 2960)—who considers the Coast Ranges and Great Valley subduction zones, along with the southern California subduction zone, to have

all been parts of a single 2,000+ mile-long oceanic trench during Mesozoic time—has concluded that

> ...the cumulative offset of these subduction zones by the San Andreas appears to be approximately 150 mi greater than the ±300 mi offset of the Late Cretaceous Great Valley sequence (Hill and Hobson, 1968), thus indicating that the period of subduction was over long before the Upper Cretaceous strata were deposited.

Hill's model offers one explanation for the juxtaposition of the contrasting terranes. However, the timing of the events, which implies a "±100 million year history of right slip" on the San Andreas fault, is one of the most controversial aspects of Hill's proposal. In addition, as Hill admits (1971, p. 2960), the problems due to the presence of the Transverse Ranges athwart the trend of the inferred single subduction zone have been ignored.

The Newport-Inglewood structural zone is commonly considered to be a member of the family of northwest-trending faults that make up the San Andreas "system" (Moody and Hill, 1956; Crowell, 1962, p. 4). The problems of the actual age of this system (see Atwater, 1970, p. 3516-3517) and the inception of right-lateral movement, therefore, contribute to the uncertainties about the early tectonic history of the Newport-Inglewood structural zone. In this regard, a factor which favors the thrust-faulting concept is that strike-slip faulting in southern California apparently did not become the dominant structural style until well into Tertiary time.

Crowell (1962, p. 49-50) has pointed out that:

> In southern California the total displacement on the combined San Gabriel and San Andreas faults was probably acquired since earliest Miocene, because all rocks older than this appear to be displaced the same amount.

Indeed, for the entire San Andreas fault, with the exception of the inferred offset of subduction zones or the granite-Franciscan assemblage contact (Hill and Dibblee, 1953; Hill and Hobson, 1968; Hill, 1971), there is only suggestive evidence for offsets of pre-Oligocene features (Grantz and Dickinson, 1968, p. 119). Furthermore, within the central Transverse Ranges, Crowell has stated (1968, p. 328) the "present knowledge in the Transverse Ranges allows the tentative conclusion that the San Andreas system is younger than about 22 or 24 m.y. (early Miocene)..."

Recently, applying the concepts of plate tectonics, Atwater (1970) has stated that "no part of the San Andreas system began movement in the present sense and rate before 30 m.y. ago" (p. 3516). The conflict between this observation and the suggestive data that appear to require the existence of a right-lateral strike-slip fault zone similar to the San Andreas prior to Miocene time has led to the postulation of a "pre-" or "proto-San Andreas fault" (Suppe, 1970, p. 3255; Atwater, 1970, p. 3517). In an effort to resolve the contradictory evidence for the inferred total slip along the San Andreas fault north and south of the Transverse Ranges, which estimates place at almost twice as much north of the Transverse Ranges as to the south, Suppe (1970) proposed a two-stage model for the movement history of the San Andreas system. In his model, Suppe (1970, p. 3255) has equated the Newport-Inglewood zone "out of convenience with the 'proto-San Andreas' because it is the boundary between basement rocks of the continental borderland and those of the southern California Peninsular Ranges" and inferred that about 280 miles of right slip occurred along this fault zone before late Oligocene time (his figure 1c). As is true of Hill's (1971) hypothesis, Suppe's reconstruction essentially ignores the structures of the Transverse Ranges which geometrically and spatially do not permit this interpretation.

The time available for the juxtaposition of the basement terranes (see quote above from Yerkes *et al.*, 1965, p. A16) spans the interval between early Late Cretaceous (about 100 million years ago) and early middle Miocene (Relizian Stage of Kleinpell (1938); at about 20 million years ago) or approximately 80 million years--a time span four times as long as the interval from the middle Miocene to the present. If the Newport-Inglewood structural zone is a member of the San Andreas system and it moves today in response to forces related to the San Andreas fault, its pre-Miocene activity (if, indeed, there was any) was probably not of the strike-slip style.

Geophysical methods, along with projections drawn from areas where wells have been drilled, give reasonably accurate estimates of the thickness of sedimentary fill in the Los Angeles basin. However, because of the wide range of specific gravities determined for specimens of basement rocks from the basin (Schoellhamer and Woodford, 1951), the location and attitude of an inferred boundary between two types of basement rock along the Newport-Inglewood structural zone cannot be determined on the basis of gravity data. Where available, seismic data, especially accurate determinations of the location and depths of earthquake foci, such as recently commenced by Teng and Real (1972), may be helpful in delineating the width and attitude of the zone. The aftershocks of the Long Beach earthquake were concentrated in a relatively narrow belt along the zone.

Just as is the case with the San Andreas and associated faults, large components of dip slip apparently have taken place along faults of the Newport-Inglewood zone. Indications of this, in addition to the possible juxtaposition of unlike basement rocks, come from "negative evidence" of the early history of the zone. Tremendous vertical movements must have taken place during the short interval between the deposition of pre-middle Miocene strata and the exposure of the Catalina Schist in the vicinity of the San Joaquin Hills. According to Yerkes *et al.* (1965, p. A16):

> ...the presence of almost 14,000 feet of pre-middle Miocene strata in the San Joaquin Hills just northeast of the Newport-Inglewood zone suggests that these strata must once have extended southwestward across the present site of the fault zone.

The Catalina Schist became exposed during the middle Miocene as evidenced by its presence as clasts in the San Onofre Breccia in the San Joaquin Hills. In addition, clasts of Catalina Schist are found in wells in the Sunset Beach, Huntington Beach, and West Newport oil fields (Yerkes *et al.*, 1965, p. A17). San Onofre Breccia crops out farther toward the southeast along the coastal region to Oceanside. In contrast, Catalina Schist fragments are absent in the thick, extensive pre-middle Miocene section exposed in the San Joaquin Hills.

Many years ago, Woodford (1925) discussed the source area and origin of the San Onofre Breccia of the San Joaquin Hills area, concluding that it, of necessity, was derived from a landmass of high relief composed of Catalina Schist that lay to the west of the present coastline. The San Onofre Breccia thins eastward from a thickness of about 2,600 feet near the coast to a thin edge about 9 miles inland and, although since removed by erosion, it probably did not extend more than 1 or 2 miles east of the Cristianitos fault (A.O. Woodford, personal communication, 1972). The coarseness of the schist debris likewise diminishes eastward. Nevertheless, Woodford (1925, p. 241) has described a 5-foot block of schist at least 9 miles from a possible source area. Elsewhere, Paul Morton (personal communication, 1972) has observed large blocks of schist with dimensions up to 15 by 10 by 8 feet at least 6 miles from the present coastline where San Juan Creek crosses the Cristianitos fault. The San Onofre Breccia

may attain its greatest thickness in the vicinity of San Onofre Mountain where Weber (1963, p. 30) has suggested that the steeply dipping section may be 4,000 feet or more in thickness.

Many workers have suggested that the source area of uplifted Catalina Schist rose as a result of differential movement along a southeastern continuation of the Newport-Inglewood structural zone. Reed and Hollister (1936, p. 1677) were of the opinion that the importance of the San Onofre Breccia in the San Joaquin Hills "lies in the suggestion it gives that the southeastern continuation of the Newport-Inglewood structural belt has been a locus of important movements since the Middle Miocene."

The fact that Catalina Schist debris is not found in rocks older than middle Miocene and that deposits of San Onofre Breccia, in the vicinity of the Los Angeles basin, are spatially restricted along the Newport-Inglewood structural zone, in conjunction with the presence of pre-middle Miocene sedimentary rocks in the Coyote Hills and buried Anaheim nose to the south (Yerkes *et al.,* 1965, figure 8), puts serious constraints upon Yeat's hypothesis of rifting in the Los Angeles basin (see p. 42).

It should be pointed out that rocks lithologically correlative with the San Onofre Breccia have not been encountered in oil fields. Considerable difference in history is indicated for the northern as opposed to the southern portion of the zone (south of Long Beach) where about 2,600 feet of the San Onofre Brcccia is preserved in the San Joaquin Hills. Furthermore, the basement-rock type that underlies the fields along the zone north of Dominguez is presently unknown.

One of the major unanswered questions with respect to the Newport-Inglewood structural zone is its extent and trend north of the Baldwin Hills. The early maps of the zone either show the Newport-Inglewood "fault" ending in the Baldwin Hills or extending to the Santa Monica Mountains through the Beverly Hills oil field, which was assumed to lie along the zone.

Reed and Hollister (1936, p. 1677), speculating on its puzzling northern continuation, noted that the zone "is not represented either as a fault or fold in the well-exposed rocks of the [Santa Monica] Mountains." However, they did suggest (p. 1678), after pointing out that the zone "is nearly in line with the most important basement contact in the Santa Monica mountains, that between the granite of the eastern end and the supposed Triassic slate that forms the basement in most places farther west," that the zone might represent the boundary between unlike basement rocks "along its entire course."

Many regional geologic maps have been compiled for the area which includes the Newport-Inglewood zone. It is evident that on many of these the location of the "Inglewood" fault as shown on the maps in the Water-Supply Papers of the U.S. Geological Survey was adopted. This is probably because the maps which accompany the Water-Supply Papers have the largest scale yet published (with the exception of Castle's 1960 map). A careful reading of Poland *et al.* (1959, p. 69-78) reveals that these workers viewed the Newport-Inglewood zone as a belt of aligned folds and faults and that the Beverly Hills comprise the northernmost uplift along the zone. They gave two reasons for connecting the Inglewood fault of the Baldwin Hills with an extension north of Ballona Gap. Firstly, there is evidence from well data that a zone of hydraulic discontinuity, trending about N 26° W, crosses Ballona Gap and is concealed beneath deposits of Holocene age (Poland *et al.,* 1959, p. 76). Secondly, there occurs in the Cheviot Hills (referred to as Beverly Hills by Poland *et al.*) an eastward-facing topographic escarpment which is aligned with the trace of the Inglewood fault across

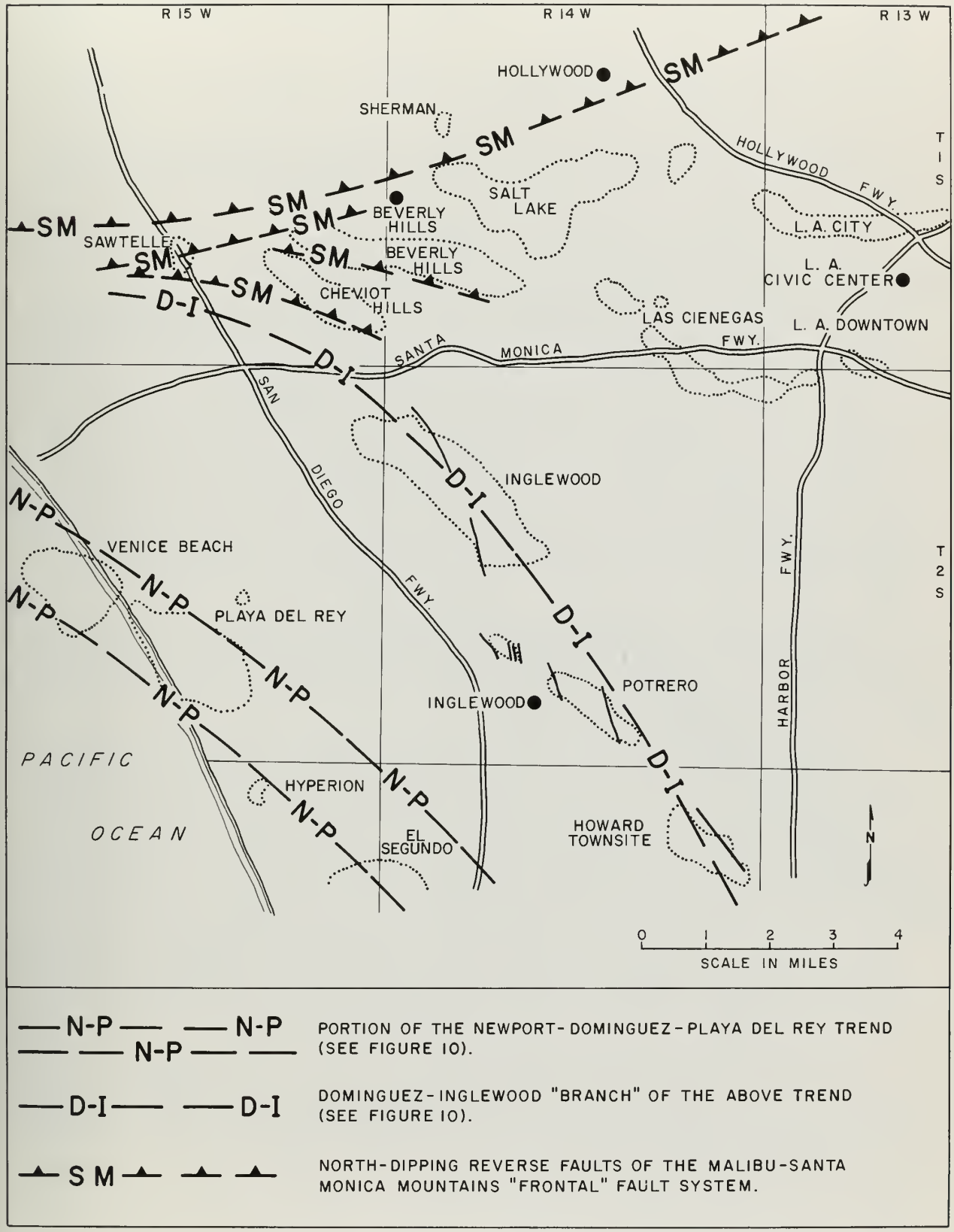

Figure 9. Speculative subsurface configuration of the major tectonic trends at the northern end of the Newport-Inglewood structural zone.

the Baldwin Hills. However, the sense of displacement on the "fault" north of Ballona Gap and the Inglewood fault in the Baldwin Hills is in the opposite direction for each segment. This led Poland *et al.* (1959, p. 76) to conclude that the "movement along the Inglewood fault must have been pivotal, with a change from downward displacement on the west in the Baldwin Hills, through a pivot of no displacement, to downward displacement on the east in Ballona Gap."

The zone of hydraulic discontinuity referred to above was long ago documented as the boundary of the artesian area in this portion of the Los Angeles basin by Mendenhall (1905, plate VI). During construction of an outfall sewer in 1924 along the foot of the north-facing slopes of the Baldwin Hills, Tieje (1926) observed a fault exposed in an excavation. There was evidence for considerable vertical displacement of the strata on either side of this fault with the eastern side being downthrown. Tieje suggested (p. 511) that "the cross-fault just mentioned diverted the course of the [ancestral Los Angeles] river [in the Ballona Creek valley] and the former flood plain became a tule bog" in which thick peat deposits formed. This circumstance, also recognized by Grant and Sheppard (1939, p. 326), implies that the surface movements on a fault which is part of the Newport-Inglewood zone are rather young. An attempt to "date the last substantial diastrophic movement along the Inglewood fault causing ponding of the ancient Los Angeles river and subsequent marsh formation" was made by Grant (*Radiocarbon,* 1965, v. 7, p. 370). The age of peat samples collected east of the fault at a depth of 10 to 15 feet down was determined by the University of California at Los Angeles using the C^{14} method to be 3420 (± 90) years. No doubt the best estimate of a minimum age of surface deformation can come only from dating the deepest peat material that represents a closer approximation to the beginning of ponding. This remains to be done.

Information from oil well drilling north of the Baldwin Hills indicates that the "Inglewood" fault which appears on the maps of Poland *et al.* (1959) in the vicinity of Ballona Creek is most likely an example of a near-surface feature commonly associated with the large fold structures along the zone.

Information from oil wells in the recently developed Cheviot Hills oil field indicates that "the northwest-trending Inglewood-Newport fault, a southwesterly dipping normal fault, is west of the field" (Crowder, 1968, p. 19). The Cheviot Hills oil field lies between the Santa Monica frontal fault system and the Newport-Inglewood structure, "which probably intersect northwest of the field" (Crowder, 1968, p. 19). This particular relation was first implied on a map by Yerkes and Wentworth (1965, figure 1). Figure 9 presents one currently permissible concept of the arrangement of the major structures in this area of complex juncture. Current drilling of deep wells in West Los Angeles and future activity wherein wells may reach basement rock will, hopefully, help resolve the problems concerning the location and structural relations between the Newport-Inglewood structural zone and the frontal fault system of the Transverse Ranges.

South of the Santa Monica Mountains and west of the Newport-Inglewood trend, the basement rock type upon which the Miocene sediments were deposited is unknown north and east of a line extending between the Dominquez and Playa del Rey-Venice area. There are only two wells which have encountered "basement" in this region, but the rock type is not recognizable as unequivocal Catalina Schist. These wells are Standard Oil's "Baldwin-Cienega" 105 in the Inglewood field and the Superior Oil Company's Inglewood Extension No. 1 which is about 2 miles east of the Playa del Rey oil field. The former is not reported to bottom in schist, and the latter well bottomed in 6 feet of "schist" (White, 1946, table 1). However, McCulloh (1970, personal communication) has stated that the Superior well bottomed in a coarse-grained carbonate

rock which is not commonly associated with the Catalina Schist. It seems best to exclude these two wells in assessing basement rock type.

A pronounced east-west trending trough is defined by the Bouguer gravity anomaly contours between the Baldwin Hills and the Santa Monica Mountains (McCulloh, 1957). Even though McCulloh (1957) suggested that the configuration of the gravity anomalies north of the Baldwin Hills supported the idea of the Beverly Hills oil field structure lying on the northern continuation of the Newport-Inglewood

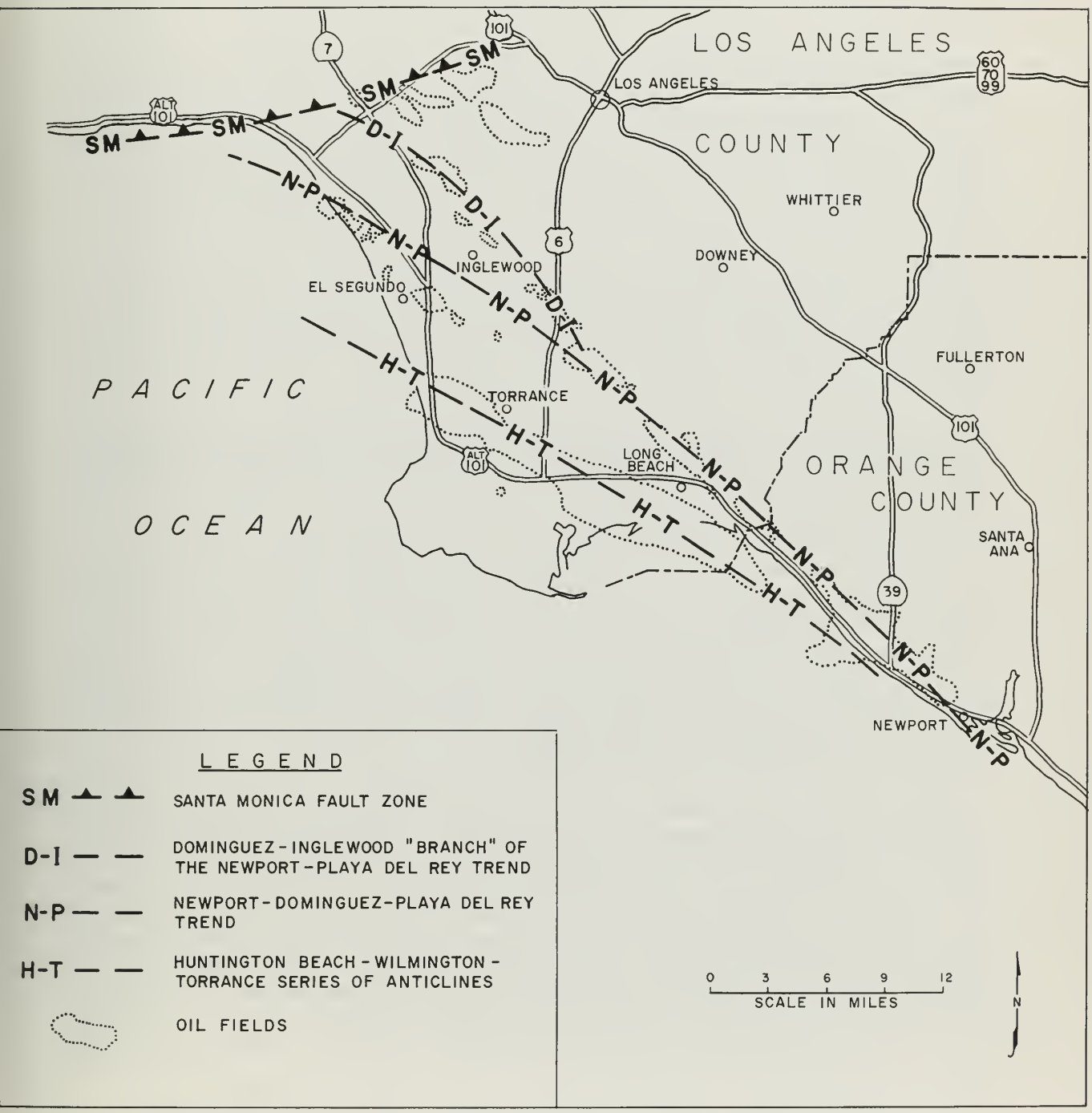

Figure 10. Possible configuration of major tectonic trends in the western Los Angeles basin.

zone, the same data can, since the discovery of the Sawtelle and Cheviot Hills fields, be used to support the concept that the Newport-Inglewood structure figuratively "dies out" or is overridden by the north-dipping reverse faults of the Santa Monica Mountains trend.

In 1960, McCulloh presented a pair of maps of the Los Angeles basin on which can be compared the gravity data and the basement-surface structure contours (his figures 150.1 and 150.2). A comparison of these maps shows that the Bouguer gravity contours do not parallel the basement structure contours in the vicinity of the Rosecrans and Inglewood oil fields. The Dominguez-Lawndale-El Segundo trend and the gravity contours are parallel, however, as can be seen on McCulloh's 1957 map.

Proposed below is an alternative interpretation to the traditional concept that the Newport-Inglewood structural zone coincides throughout its reach in the Los Angeles basin with the approximate location of the buried basement contact between Catalina Schist and crystalline basement. According to this view, the Catalina Schist and crystalline basement boundary does not coincide with the Newport-Inglewood zone as it is now conceived north of Dominguez Hills. This proposed tectonic configuration is based upon the presumed lack, noted above, of Catalina Schist basement north of the Dominguez-Playa del Rey trend and also on the change in strike of the major faults of the aligned structures from N 50° W south of Signal Hill to N 20° W north of Dominguez (see plate 1). Figure 15 presents this alternative interpretation. Bifurcations of the major faults in this portion of the Los Angeles basin have also been suggested by Willis (1923) and on a compilation in Bulletin 170 (Jahns, 1954, chapter 1, figure 12).

In figure 10, the "Newport-Playa del Rey" trend is the proposed trace of structures which overlie the buried basement contact. The other "trends" shown in figure 10 are traces of related structural alignments which do not overlie basement contacts.

The essential features of the tectonic picture which is presented in figure 10 is a westward splaying out of structural trends from a dominantly northwest-trending zone. The major fault systems south of the Transverse Ranges and west of the San Andreas fault all exhibit a similar style of behavior. Therefore, the suggested aspect of the Newport-Inglewood and other branches in its family of fault zones is an expectable one. Although the faults on the eastern side of the Los Angeles basin do not overlie buried basement contacts, they do provide a nearby example of this tectonic style. Specifically, upon approaching the Los Angeles basin, the Elsinore fault splits into two branches--the Chino and the Whittier faults.

In the section on earthquake history of the zone, it is pointed out that seismic activity along the Newport-Inglewood structural zone, exemplified by the Long Beach earthquake and its aftershock sequence, may affect only specific segments and one point at which a discontinuity in activity apparently occurs lies near Signal Hill. Recently, Richter (1970a, p. 136) reiterated the discontinuous nature of the seismic activity for different segments of the zone. The preliminary results of microearthquake monitoring studies concentrated in the vicinity of the Newport-Inglewood trend by Teng and Real (1972) of the University of Southern California reveal a clustering in 1971 within the Baldwin Hills area whereas the remainder of the events were scattered in the area to the southwest bounded by Ballona Creek, the coastline, Manhattan Beach, and Hawthorne.

It is felt, therefore, that the evidence from holes reaching basement, gravity data, seismicity, and the trends of local structures associated with individual oil fields permit

the concept that the major basement structure extends from offshore at Newport northwestwardly to Dominguez Hill where it bends more toward the west and underlies the schist "high" to the Playa del Rey oil field, finally going out to sea and merging with the Malibu Coast zone. A corollary of this hypothesis is that the segment from Dominguez Hill to Baldwin Hills does not overlie the basement boundary but is probably within eastern basement. The Newport-Playa del Rey trend lies more nearly parallel to the tectonic "grain" of the region. It parallels the seismically active Palos Verdes Hills fault zone along which the vertical separation of the basement surface is similar to that of the Cherry-Hill fault at Signal Hill.

Another major source of speculation concerns the possibility of a continuation of the zone once it disappears from view offshore at Newport Beach. A major fault lying offshore approximately parallel to the southern California coast has long been postulated. In fact, this idea is older than the recognition of the Newport-Inglewood structural zone itself. In order to explain the occurrence of earthquakes which appeared to originate beneath the sea off southern California, Wood (1916) proposed the hypothetical "San Pedro Submarine fault-zone" (see p.61). At the time, he felt that it could be only approximately located somewhere in the offshore region between Santa Barbara and San Diego.

The first map of the Newport-Inglewood zone also depicts a southeastward continuation of the zone onshore beyond Newport as far as Oceanside (Taber, 1920, plate 13; see figure 4, this paper), presumably on the basis of topography. To provide a historical perspective on the popular concept of a southeastern continuation of the Newport-Inglewood zone, a summary of the maps which portray such a configuration is given in table 2. Another early map (Willis, 1923, "Fault Map of California") shows the Newport-Inglewood "fault" going offshore at Newport but re-emerging on land at San Onofre. Table 2 shows that Eaton (1933, figure 1; see figure 16, this paper) was the first to suggest that the Newport-Inglewood zone connects with the Rose Canyon fault of the San Diego region. Table 2 also reveals that early workers generally thought the zone came back on shore in the vicinity of San Onofre or San Clemente. These early proposals are not supported by the geologic evidence in the region between Newport Beach and San Diego (Rogers, 1965).

More recently, several geologists have suggested that the Newport-Inglewood zone trends offshore at Newport Beach, roughly parallels the coastline, and connects with the Rose Canyon fault near San Diego (for example, Emery, 1960, figure 68; King, 1969). Interpretations such as these were based, for the most part, upon studies of submarine topography (Shepard and Emery, 1941). These studies revealed a scarp-like feature lying between the depths of 300 and 1,500 feet, 2 to 5 miles off the southern California coast and having the same strike as the Newport-Inglewood zone. In the absence of any detailed knowledge of the geology of the offshore area, only information on the seismicity of the region could be used to support or refute the hypothesis of a southeastern continuation of the zone. Allen *et al.* (1965, plate 1) have shown by means of a strain-release map that an inferred southeastern continuation of the zone does not coincide with a region that has been as seismically active as the portion which lies in the Los Angeles basin. An earthquake of magnitude 4.3 occurred about 3 1/4 miles west-southwest of Laguna Beach on October 27, 1969. The epicenter was approximately located at the base of the 1,500-foot submarine escarpment and, in the opinion of Richter (1970a, p. 136), "indicates extension of seismicity [about 10 miles] southeastward beyond the main epicenter of 1933."

One major aspect of onshore geology to be considered in any analysis of a possible continuation of the Newport-Inglewood zone involves the proximity to the source area of the Catalina Schist debris in the San Onofre Breccia. The distribution, thickness, and

Table 2. Fault maps showing an inferred southeastern extension of the Newport-Inglewood zone.

Reference	*Remarks*	*Location in this paper*
Taber, 1920, Plate 13	Map shows "Inglewood-Newport-San Onofre fault" entirely on land as far south as Oceanside—a total length of 85 miles; drawn on basis of topography (p. 141).	Figure 4
Willis, 1923, "A fault map of California": Bulletin of the Seismological Society of America, v. 13, p. 1–12, explanation	Newport-Inglewood fault is shown going offshore at Newport, paralleling the coast, coming back onshore at San Onofre, and trending in a straight line as far south as Escondido.	Not shown
Willis, 1923–24, v. 13, plates 8, 9, 12; v. 14, Plate 4	Bifurcating Newport-Inglewood fault shown offshore from Long Beach to Dana Point where map ends (v. 14, Plate 4). Plates 8, 9, and 12 (v. 13) show the extension of the zone either at the shoreline or trending inland so that it is several miles east of San Diego.	Figure 6 reproduces Plate 4, v. 14
Ferguson and Willis, 1924, Figure 1	Shows fault just offshore only as far south as San Joaquin Hills.	Figure 7
Vickery, 1928, p. 357	Shows fault parallel to coastline exactly at coastline only as far south as San Joaquin Hills.	Figure 8
Eaton, 1933, Figure 1	Inset in this figure is first regional map to show Newport-Inglewood fault connected by an offshore extension with the Rose Canyon fault at San Diego.	Figure 16
Willis, 1938, Figure 1	This map (on which Willis called the Newport-Inglewood zone the "San Pedro fault zone") is larger scale but similar to the 1923-24 Plates 8 and 12. Fault goes onshore at San Onofre and is shown 15 to 20 miles east of San Diego.	Not shown
Shepard and Emery, 1941	Do not show on their charts but state in text (p. 26): "The topography on the sea floor suggests a southward continuation of the supposed fault since the inset portion of the submarine scarp appears to be in direct line with the so-called Inglewood fault".	Not shown
Wood, 1947, Maps 2, 3, 4	Maps show proposed continuation of the Newport-Inglewood fault going onshore in vicinity of San Clemente.	Not shown
Clements and Emery, 1947	They state (p. 310): "A scarp about 1,500 feet in height that extends southeastward from Newport Beach and gradually flattens out near Oceanside is marked by a few scattered epicenters and can only doubtfully be considered a continuation of the Inglewood fault".	Not shown
Corey, 1954, Bulletin 170, chapter 3, part B, Figures 1–8	These maps show the Newport-Inglewood fault going offshore at Newport Beach, trending very close to the coastline, and joining a more northerly fault south of San Onofre. The latter fault connects the Cristianitos and Rose Canyon faults.	Not shown
Emery, 1960, Plate 68	Map shows major fault zone following the 1,500-foot depth contour from Newport to the La Jolla submarine canyon where it joins the Rose Canyon fault, crosses Coronado, and heads offshore parallel to the Baja California coast.	Not shown
Allen, St. Amand, Richter, and Nordquist, 1965, Plate 1	Map is similar to Emery's 1960 map: the southern section of the projected fault is not extended to Coronado.	Not shown
Albee and Smith, 1966, Figure 9	Map is generalized from Emery (1960) and Allen *et al.* (1965).	Not shown
Minch, 1967, Figure 7	Map is generalized from Emery (1960) and Allen *et al.* (1965).	Not shown
King, 1969, Tectonic map of North America	Very small scale map shows faults in continental borderland probably modified from Emery (1960) and Allen *et al.* (1965).	Not shown
Parker, 1971, Figures 3, 4, 5	Maps depicting major faults of the continental borderland show "Inglewood-Newport fault" extending southeastward nearly to Oceanside essentially identical to Emery's 1960 map.	Not shown

coarseness of the breccia (see discussion on pages 45-46) are factors that provide clues to the nearness of the source area. As a corollary to the inference that the Newport-Inglewood zone within the Los Angeles basin overlies the boundary between Catalina Schist and eastern granitic basement (see pages 45-46), a continuation of this contact to the southeast is implied by features of the breccia.

Consideration of the hypothesis that the Newport-Inglewood zone continues southeastward from Newport Beach beneath the sea toward San Diego as described above is one of the main topics included in an analysis of the regional geology surrounding the San Onofre Nuclear Generating Station in the application by the power companies for a permit to expand the facility. A wealth of geophysical data has been assembled, reviewed, and analyzed by the applicants in their Preliminary Safety Analysis Report (1972, Amendment 11, Appendix 2E). This document makes use of a report prepared by consultants retained by the applicants on the offshore geological structure (Jahns *et al.*, 1971) and of a subsequent study prepared by Western Geophysical Company of America (PSAR, 1972, Amendment 11, Appendix 2E, Attachment 1).

The earlier investigations (Jahns *et al.*, 1971) of the offshore geology in the region between Newport Beach and San Diego were based upon sparker-profiling techniques which penetrate to shallow depths (hundreds of feet) beneath the sea floor. The relevant conclusions with respect to the present discussion, based upon the shallow-depth data, were that the "principal structural feature of the continental shelf off San Onofre is a large anticline and an associated syncline about four or five miles offshore" the axis of which is approximately coincident with the edge of the shelf and "there is no evidence for a continuous shelf-edge fault" (Jahns *et al.*, 1971, p. 6). The consultants also concluded from the profiling data that "the anticline is discontinuously broken along parts of its length by short faults near its axis. These faults have not produced pronounced displacement of strata, nor have they displaced the sea floor" (Jahns *et al.*, 1971, p. 9).

The offshore structures can be compared and contrasted to the "Newport-Inglewood zone of deformation" from the description given by Jahns *et al.* (1971, p. 11):

> In the subsurface the zone includes many sub-parallel faults, some of them entirely separate and others branching and joining. None of the faults are continuous for more than a fraction of the length of the zone, and the zone includes no single clear-cut surface feature that can be identified as 'the Newport-Inglewood fault'.

The tectonic activity and seismicity of the zone were also summarized by Jahns *et al.* (1971, p. 13):

> Activity has continued through the remainder of Cenozoic time, and historic seismicity bespeaks present activity despite facts that (1) no member of the fault complex is known to cut strata younger than late Pleistocene, and (2) no surface ground displacement is known to have accompanied historic earthquakes associated with the zone.

Jahns *et al.* (1971, p. 14-15) concluded that the Newport-Inglewood zone terminates somewhere offshore between Newport Beach and Laguna Beach because they could detect no topographic expression on the sea floor, no "continuous zone of folds and faults" from the seismic reflection profiling; and southeast of Laguna Beach there is lack of seismic activity similar to that in the Los Angeles basin for the Newport-Inglewood zone. They did conclude, however, that the buried basement boundary inferred to underlie the Newport-Inglewood zone does continue toward the southeast as the Southern California subduction zone (also Hill, 1971).

Investigations conducted by the investigators in the earlier studies were simply not adequate in critical areas to confirm or disprove the hypothesis that the structural features which were revealed are indeed not extensions of the Newport-Inglewood zone, differing from the structures in the Los Angeles basin because of their subsea rather than subaerial erosional and depositional environment. A knowledge of the geologic structure to much greater depths than could be reached by the techniques employed up to that time was necessary.

The subsequent studies (PSAR, 1972, Amendment 11, Appendix 2E) are based upon a wealth of data derived from deep-penetration seismic reflection profiling (10,000 feet or more beneath the sea floor), analyses of regional gravity and magnetic information, three offshore core holes, and seismic refraction traverses. The resolving power of some of these techniques along with the large volume of data make it possible to produce interpretive maps of the geologic structure in portions of the offshore area down to basement rock depths. One of these maps (PSAR, 1972, figure 2E-2) depicts the configuration of the surface of "acoustic basement" otherwise known as "Horizon C" which is assumed to consist, depending on the region, either of continental basement (such as occurs in the Peninsular Ranges) on the southeast, San Onofre Breccia in the central portion, and Catalina Schist on the northwest with structure contours based upon reflection times and not depths. Another map (PSAR, 1972, figure 2E-3) shows the surface of "Horizon B" which is also contoured in reflection times and is assumed by correlation with core-hole data to be a sedimentary unit "within Upper Miocene." Finally, a topographic map of the sea floor (Horizon A) completes the set (PSAR, 1972, figure 2E-4A).

Essentially, for purposes of this report, the structural feature of most importance to be interpreted from these maps is the "South Coast Offshore fault" which "has apparent vertical displacement of the acoustic basement (Horizon C) in the order of 2000 to 3000 feet" down on the southwest and extends about 40 miles from the vicinity of Laguna Beach to Carlsbad. The South Coast Offshore fault consists of about 29 miles of "discontinuous short-fault segments" that offset Horizon B vertically "mostly on the order of a few hundred feet" (PSAR, 1972, p. 2E-6). The strike and location of the South Coast Offshore fault coincide, in general, with the edge of the shelf which is about 4 or 5 miles off San Onofre but closer to the coast at Laguna Beach and Oceanside.

The major question to be answered is: *Does the South Coast Offshore fault represent a continuation of the Newport-Inglewood structural zone or is it a separate unrelated feature?* The conclusion of the consultants for the applicants (PSAR, 1972, p. 2E-9) is that the South Coast Offshore fault

> ...is neither a continuation of the Newport-Inglewood Zone to the northwest, nor of the Rose Canyon fault to the southeast. The South Coast Offshore fault dies out along its strike and upward (fig. 2E-6) and has no expression on the ocean floor. The limited length of this fault and the small vertical displacement across it in Horizon B indicate that its effect is significantly less in the younger (Upper Miocene) rocks.

Many aspects of the Newport-Inglewood structural zone and the South Coast Offshore fault are compared in table 3, which summarizes the important similarities in gross structural aspects and a history of diminishing tectonic activity toward the present characterized by short-fault segments of a discontinuous nature. Implications of other aspects listed in table 3 include the possible association of the Newport-Inglewood and South Coast structures with the tectonic conditions reponsible for the creation of a western highland during middle Miocene time which contributed Catalina Schist debris to the San Onofre Breccia. The relation of either of the zones to an inferred basement-rock boundary has not been proved. For the Newport-Inglewood structural zone it is

Table 3. Comparison of the Newport-Inglewood structural zone of the Los Angeles Basin with the South Coast Offshore fault.

Aspect compared	*Newport-Inglewood structural zone*	*South Coast Offshore fault*
Dimensions	Approximately 40 miles long by ½ to 3 miles wide.	Approximately 41 miles long by ½ to 2 miles wide.
Trend or regional strike	N 45° W	N 40° W
Oldest post-basement rocks displaced	Middle Miocene marine sedimentary rocks.	Possibly as old as Cretaceous(?)(P.S.A.R., 1972, fig. 2E-13).
Surface expression	Alignment of low hills and mesas separated by several gaps; total relief only 513 feet; locally, fault-line scarps.	". . . no expression on ocean floor" (P.S.A.R., 1972, p. 2E-9). However, edge of continental shelf overlies the buried fault (P.S.A.R., 1972, fig. 2E-12; fig. 2E-13; Attachment 1, p. 33).
Shallow depth expression	No evidence of post-Pleistocene surface displacement; numerous, interrupted minor faults associated with individual uplifts total about 24 miles at the surface.	"Discontinuous short-fault segments . . . display vertical offset of Horizon B, mostly on the order of a few hundred feet" (P.S.A.R., 1972, p. 2E-6). Segments total about 29 miles.
Continuity	Not continuous in the sedimentary strata; inferred to be continuous in the basement on the basis of seismic data.	Not continuous in the sedimentary section (Horizon B, Upper Miocene) but interpreted to be a continuous fault in "acoustic basement" which is locally middle Miocene San Onofre Breccia not geologic basement.
Maximum vertical separation	4,000 feet at basement surface (Long Beach oil field); 1,000 feet in Pliocene strata; 200 feet base of Pleistocene; all down on southwest (Yerkes *et al.*, 1965, p. A48).	5,500 feet on "acoustic basement" but "does not exceed 3,000 feet over most of its length" (P.S.A.R., 1972, Attachment 1, p. 40); as much as 600 to 700 feet on highest definitive reflector (Horizon B or Upper Miocene); up to 1,000 feet sediment undisturbed over fault (Line 115) all down on southwest.
Maximum horizontal separation	Right-lateral strike-slip displacement of lower Pliocene from 3,000 to 5,000 feet (Yerkes *et al.*, 1965, p. A48). Up to 10,000 feet right-lateral slip (Hill, 1971, p. 2958).	Possible right-lateral offset on axis of San Joaquin Hills structural high up to 7,000 feet (P.S.A.R., 1972, Attachment 1, p. 40).
Local structural features	Horst under Long Beach oil field at approximately the mid-point of the zone; basement is down approximately 4,000 feet on the west and 1,000 feet down on east (Yerkes *et al.*, 1965, pl. 1.44).	Horst about 5 miles west of San Onofre, at approximately the mid-point of the zone; "acoustic basement" down approximately 1,600 feet on west and 2,400 feet on east (P.S.A.R., 1972, fig. 2E-7).
Seismicity	Earthquakes are abundant and frequent and relatively evenly distributed along the zone; pattern of activity suggests association with local segments (Richter, 1970a); includes damaging 1920 Inglewood earthquake and 1933 Long Beach earthquake.	"There is no macroseismicity associated with the fault" (P.S.A.R., 1972, p. 2E-18); also "no evidence has been found . . . of surface rupture or offset of geomorphic features, or to suggest post-Miocene or Quaternary activity on the fault." However, 1969 4.5 magnitude earthquake off Laguna Beach plots directly on the fault.
Relation to San Onofre Breccia	Zone might have coincided in middle Miocene time with the eastern boundary of the highland from which Catalina Schist debris was derived based on coarseness and distribution of the breccia.	Fault is a likely distance from the present exposures of San Onofre Breccia to represent the boundary of the schist high, more likely than the interpretation of P.S.A.R., (1972, fig. 2E-12) wherein huge blocks of schist now 7 and 8 miles inland would had to have traveled 18 miles.

....*continued on page following*

Table 3. Comparison of the Newport-Inglewood structural zone of the Los Angeles Basin with the South Coast Offshore fault —Continued

Aspect compared	*Newport-Inglewood structural zone*	*South Coast Offshore fault*
Relation to buried basement boundary	Inferred to overlie buried basement boundary but parallel basement boundary could be 1.5 miles to the northeast on basis of gravity data (Yerkes *et al.*, 1965, p. A48).	Basement boundary off southern California has been named the southern California subduction zone (Hill, 1971). Locus of subduction zone interpreted from gravity anomaly gradients to be 15 to 18 miles offshore, offset by the San Joaquin Hills Offshore high and not to underlie the South Coast Offshore fault (P.S.A.R., 1972, Attachment 1, p. 37).
Correlation with Bouguer gravity anomaly data	Overlies a steep Bouguer anomaly gradient of −40 to −20 milligals. This gradient has been interpreted to mean that different types of basement rock are juxtaposed here. However, "empirical comparisons of densities of the two major basement rock types reveal no significant density differences in the material accessible to sampling (T. H. McCulloh, personal communication)" (Harrison *et al.*, 1966, p. 4935).	Western Geophysical Co. of America has interpreted gravity data from Harrison *et al.*, (1966). They interpret the steeper gradients between negative and positive Bouguer anomaly values to "define the position of the subduction zone" (P.S.A.R., 1972, Attachment 1, p. 22).
Evidence for termination at ends	Appears to be overridden by reverse faults associated with the Santa Monica-Malibu Coast fault system on the north; becomes dispersed and broadens out in the Newport Beach area and it may be terminated by the San Joaquin Hills Offshore high or it may just be difficult to trace through this area.	Displacement, determined from seismic profiling data, appears to die out toward both ends as well as upward in this section. Northern end may be cut off by a northerly trending fault in the San Joaquin Hills Offshore high. Southern end interpreted as "dying out" near Rose Canyon fault.

possible that the boundary lies to the east of the zone (see table 3) and may even underlie the central deep of the Los Angeles basin. For the South Coast Offshore fault (which has been interpreted by the applicants as lying 5 to 7 miles east of the southern California subduction zone) it must be pointed out that the "acoustic basement" in the vicinity of much of the fault is not geologic basement (which is unknown) but is assumed to be Middle Miocene San Onofre Breccia. Furthermore, the argument that what is eastern and what is western basement can be determined on the basis of gravity data is weakened by the fact that assumed density differences in the basement-rock terranes cannot be demonstrated (see table 3). Therefore, it is possible that the offshore fault may overlie the subduction zone.

The most important contrast between the two structural features is in their historical and recorded seismic activity or inactivity. The significance of recorded earthquakes or lack of them is questionable because of the short time that seismographs have been in operation in southern California. There is, in addition, the possibility that activity along the Newport-Inglewood zone may be locally restricted to various segments (Richter, 1970a) as was demonstrated by the 1933 Long Beach earthquake. A problem with the earthquake history is the impossibility of locating the epicenter of early historic events such as the damaging earthquake of December 8, 1812, that killed 40 people at San Juan Capistrano. Wood (1916) has suggested that events such as this could have been the result of earthquakes located at sea (see page 61 this paper). The applicants concluded (PSAR, 1972, p. 2, 10-4) that "no earthquake epicenters can be associated with the Newport-Inglewood zone farther southeast than the 1969, magnitude 4.5, event offshore from Laguna Beach." However, as table 3 points out, this particular event occurred on what is shown on their maps as the South Coast Offshore fault. This suggests that either the Newport-Inglewood zone is continuous beyond its so-called termination with the South Coast Offshore fault or that the offshore fault is seismically active at its northwestern end.

In support of the conclusions about seismic inactivity based on the short historic record and paucity of instrumentally recorded events is the evidence implying tectonic quiescence demonstrated by the locally thick (up to 1,000 feet) undisturbed strata of unknown age overlying the offshore fault in subbottom profiles. The unknown age of the apparently undisturbed (within the resolving power of the profiling techniques) sediments is an important point because in the subaerial erosional environment which influences the topographic expression along the Newport-Inglewood zone material has been eroded away thereby creating fault-line scarps, none of which cuts deposits younger than Late Pleistocene. Does this mean that, if the Newport-Inglewood zone was also under water and subjected to similar conditions to the South Coast Offshore fault, it would display its relatively minor relief (maximum of 511 feet in the Baldwin Hills)? There is currently no good explanation either for the development of the edge of the continental shelf or for the coincidence of the trend of the offshore fault with this shelf edge.

Contrary to the interpretation of the applicants, as quoted above, the disassociation of the Newport-Inglewood structural zone and the South Coast Offshore fault does not seem to be warranted. The similarities (table 3) provide a cogent argument for concluding that the Newport-Inglewood structural zone does extend offshore parallel to the southern California coast and that the South Coast Offshore fault is a continuation of the Newport-Inglewood zone.

EARTHQUAKE HISTORY

Although southern California has been seismically very active during the past 200 years, written accounts of only the strongest shocks survive the early part of this period. However, early descriptions of earthquakes are rarely specific enough to allow an association with any particular fault zone. It is also not possible to locate "accurately" epicenters of earthquakes which occurred prior to the twentieth century.

Among the catalogs of earthquakes that have occurred in southern California since 1769 (Holden, 1897; Wood, 1916; Townley and Allen, 1939), the most complete is that of Townley and Allen, which covers the period from 1769 to 1928. This catalog reveals that, of the approximately 53 earthquakes recorded as being felt in the Los Angeles area before 1917, 17 might have been associated with the Newport-Inglewood zone (see table 4). However, because the association between faults and earthquakes was not known and the Newport-Inglewood zone in particular had not been recognized, correlation of shocks with the zone is, naturally, speculative. The table shows that most earthquakes were of low intensity and not demonstratively associated with the structural zones along the western portion of the Los Angeles basin.

Table 4. Pre-1928 earthquake history of Los Angeles area.

Date	*Locality data*	*Intensity (Rossi-Forel scale)*	*Origin on Newport-Inglewood zone**		
			Possible	*Probable*	*Known*
1769 July 28	Los Angeles region	VI?; X?	?		
1812 Dec. 8	Southern California coast	(M.M. scale) VIII–IX	?		
1827 Sept. 23	Los Angeles	?	?		
1848 Jan. 4	Los Angeles	?			
1852 Nov. 20	Los Angeles; 32 shocks	?			
1852 Dec. 26	Los Angeles	?			
1855 July 10	Los Angeles County (offshore?)	VIII	?		
1856 April 6; April 14; May 2; May 9	Los Angeles	?			
1857 Jan. 16; Jan. 17	Los Angeles	?			
1857 May 2	Los Angeles	?			
1860 Jan. 26–27	Los Angeles, night	"severe shock"	?		
1860 March 26	Los Angeles	?	?		
1862 June 7	Los Angeles	?			
1864 July 18	Los Angeles	?	?		
1864 July 25	Los Angeles	?			
1869 October	Los Angeles	?			
1877 Sept. 19	Los Angeles	?			
1878 June 11–12	Los Angeles; 4 shocks	III, V, III, I	?	?	
1878 Late summer	Inglewood (W. Mulholland B.S.S.A., v. 10)	(M.M. scale) VIII		X	
1879 Aug. 10	San Fernando; "tidal wave at Santa Monica"	IV?; V?	X	?	
1879 Dec. 7	Los Angeles	III			
1880 March 21	Los Angeles	V			
1880 April 12	Los Angeles; most severe on San Gabriel River	V			
1880 Sept. 26	Los Angeles	?			
1880 Nov. 12	Los Angeles	III			
1880 Nov. 21	Los Angeles and south and east of Angeles; 3 shocks	?	?		
1880 Dec. 19	Los Angeles and San Diego	V	?		
1881 April 27	Los Angeles	?			
1882 Sept. 7	Los Angeles	?			
1883 Jan. 23	Los Angeles	III			
1883 July 7	Los Angeles	II			
1883 Sept. 1	Los Angeles	III			
1883 Sept. 5	Los Angeles, Santa Barbara, Wilmington, Ventura	VI			

....continued on page following

Table 4. Pre-1928 earthquake history of Los Angeles area —Continued

Date	Locality data	Intensity (Rossi-Forel scale)	Origin on Newport-Inglewood zone*		
			Possible	Probable	Known
1917 June 24	Los Angeles (12:30 p.m.)	III to IV		X	
1917 June 25	Los Angeles (8:15 p.m.)	III to IV		X	
1917 June 25	Los Angeles (8:24 p.m.), southern portion of city	IV to V		X	
1917 June 26	Los Angeles (3:51 a.m.) trembling motion	III		X	
1917 June 26	Los Angeles; strongest in southern part of city (1:15 p.m., 1:20 p.m., 1:30 p.m.)	V to VI		X	
1917 June 28	Los Angeles; rumbling	IV		X	
1917 June 29	Los Angeles; trembling	III to IV		X	
1917 June 30	Los Angeles, southern part	IV		X	
1883 Dec. 12	Los Angeles	III			
1883 Dec. 13	Los Angeles	?			
1884 Jan. 4	Los Angeles	III			
1884 June 16	Los Angeles	?			
1884 Oct. 22	Los Angeles	III			
1885 June 14	Los Angeles	?			
1885 Sept. 13	Southern California: Los Angeles to San Diego to San Bernardino	IV	?		
1887 May 3	Los Angeles	"not felt"			
1889 Aug. 27	Southern California: lighter in Santa Monica and San Bernardino than in Pomona	VII			
1890 Feb. 9	Southern California; 3 shocks at San Pedro; long and steady vibration at Los Angeles "center near San Jacinto"	VI–VII			
1893 May 18	Southern California coast region; "most severe southeast of Ventura"	VII?	?		
1894 Feb. 8	Los Angeles; only one sharp shock	?			
1894 July 29	Southern California; 2 shocks at Santa Monica; "last heaviest ever felt there"	VII	?		
1896 Feb. 15	Los Angeles	?			
1898 June 30	Los Angeles	"sharp"			
1904 Oct. 15	Los Angeles	"light shock"			
1906 April 19	San Pedro	?	?		
1906 April 19	Los Angeles; 2 shocks	?			
1906 April 19	Los Angeles; 2 shocks and light tremors	?			
1906 April 20	Santa Monica	?	?		
1917 Feb. 13	Los Angeles and southwest of business district	V to VI		X	
1917 June 9	Los Angeles; noticed in southwest portion of city	"felt"		X	
1917 June 24	Los Angeles (12 p.m.)	III to IV		X	
1917 July 15	Los Angeles	"slight"	?		
1917 July 17	Los Angeles; 3 shocks, swaying	IV	X	?	
1917 Aug. 3	Los Angeles; rocking motion	III	X	?	
1917 Nov. 23	Los Angeles; southwestern part of city	II to III		X	
1918 March 6	Los Angeles region; most severe in Venice and Santa Monica	V to VI	?		
1918 March 8	Venice and Ocean Park; bumping and rumblings	IV to V	?		
1918 Sept. 16	Los Angeles 20 seconds	III			
1918 Nov. 19	Santa Monica Bay region, Venice, Long Beach, Pomona	VI to VII	X		
1919 Feb. 9?	San Pedro(?)(may be wrong)	?			
1919 Dec. 18	Los Angeles ("prolonged")	III			
1920 Feb. 22	Sawtelle (west Los Angeles)	VI		X	
1920 Feb. 23	Sawtelle	"felt by several"	X	?	
1920 March 3	El Segundo, Manhattan Beach, Redondo Beach	III to IV	?		
1920 March 16	Sawtelle (5 shocks)	III	X	?	
1920 March 24	Sawtelle (2 shocks)	"felt by several"	X	?	
1920 April 17	Sawtelle	"felt by several"	X	?	
1920 April 22	Sawtelle; northwest to southeast motion	"felt by several"	X	?	
1920 April 30	Sawtelle	"light"	X		
1920 May 4	Sawtelle	"light"	X		

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Table 4. Pre-1928 earthquake history of Los Angeles area —Continued

Date	Locality data	Intensity (Rossi-Forel scale)	Origin on Newport-Inglewood zone*		
			Possible	Probable	Known
1920 May 18	Santa Monica; abrupt bumping; southwest to northeast motion	III	X		
1920 May 21	Sawtelle	III	X		
1920 June 18	Los Angeles region (2:08 a.m.); possible origin at sea in San Pedro channel	"Seismograms show about = VIII"	?	?	
1920 June 18 or 19	Inglewood (10:30 a.m.)	"light"		X	
1920 June 21	Inglewood, early afternoon (fore-shocks)	"light shocks"			X
1920 June 21	"Inglewood earthquake" (6:48 p.m.)	VIII to IX			X
1920 June 22	Inglewood (2:30 a.m.)	"2 strong shocks"			X
1920 June 22	Near Inglewood also Torrance (4:00 a.m.)	"strong"			X
1920 June 22	Inglewood (5:00 a.m.)	?			X
1920 June 22	Inglewood (12:35 p.m.)	V			X
1920 June 22	Inglewood (9:09 p.m.)	"sharp"			X
1920 June 23	Inglewood (4:06 a.m.)	"sharp"			X
1920 June 23	Inglewood (6:51 a.m., 2:10 p.m., 2:24 p.m.)	"all very light"			X
1920 June 24	Inglewood	"light"			X
1920 June 29	Inglewood	V			X
1920 June 29	Los Angeles (possibly previous shock)	III			X
1920 July 10	Los Angeles	III to IV	?		
1920 July 10	Series of extremely localized shocks northwest of Los Angeles business district	II to VII			
1920 July 19	Los Angeles	II to III			
1920 July 20	Los Angeles	III			
1920 July 26	Los Angeles (4 shocks)	II to V			
1920 July 27	Los Angeles (5 shocks)	II to III			
1920 July 28	Los Angeles	IV			
1920 July 29	Los Angeles	IV			
1920 Aug. 23	Los Angeles (2 or 3 shocks); bumping	IV			
1920 Sept. 2	Los Angeles (3 shocks)	II			
1920 Sept 3	Los Angeles	II			
1920 Sept 15	Los Angeles (3 shocks)	II			
1920 Sept. 18	Los Angeles	III			
1920 Dec. 6	Los Angeles (3 shocks)	III			
1920 Dec. 27	Los Angeles and Inglewood (2 shocks)	III	X		
1921 April 21	Hollywood and Los Angeles	III to V			
1921 May 2	Los Angeles; duration 7 to 10 seconds	III			
1921 May 4	Los Angeles	II			
1922 Jan. 17	Los Angeles and Pomona; "probably gunfire"	"slight"			
1923 Nov. 8	Los Angeles region; 2 to 12 light shocks	"light shocks"			
1923 Dec. 6	Southern Los Angeles County; from coast, east to Whittier	?	?		
1924 Jan. 2	Los Angeles region	"slight"			
1925 Jan. 10	Los Angeles and vicinity	"slight"			
1925 March 2	Long Beach	III	?		
1925 May 1	Southern California coast; Long Beach	IV	X	?	
1925 June 12	Los Angeles; abrupt, felt in nearby towns	III+?			
1926 Dec. 29	Redondo Beach; north-northwest to south-southeast; reported in Los Angeles, too	IV	?		
1927 Jan. 29	Sawtelle; felt as far as Riverside; origin near Sawtelle	IV or V	X	?	
1927 Feb. 4	Santa Monica Bay	"jolt"			
1927 Feb. 6	VI in Sawtelle V to VI in southwest Los Angeles; sharp in Santa Monica	VI	X	?	
1927 April 15	Los Angeles region; strongest at beaches southwest of Los Angeles	"rattling of buildings"	X	?	
1927 Aug. 4	Santa Monica Bay; origin under bay	VI+?			
1927 Aug. 4	Los Angeles and neighboring towns reported that the shock brought in an oil well which was being drilled near Long Beach	?	?		

....continued on page following

Table 4. Pre-1928 earthquake history of Los Angeles area —Continued

Date	Locality data	Intensity (Rossi-Forel scale)	Origin on Newport-Inglewood zone*		
			Possible	Probable	Known
1927 Oct. 8	Origin east of Compton	VI	?		
1927 Dec. 10	Inglewood? "source same as that of 1920 shocks"	?		X	?
1927 Dec. 15	Near Torrance; origin southeast of Dec. 10 quake	?	X	?	
1927 Dec. 31	Santa Monica Bay; origin under bay	?			

* Where specific information is totally lacking, no mark was placed in the "Possible" or "Probable" columns; where some information suggests that movements along the zone may have been responsible for a shock, a question mark was placed in the "Possible" column; where the connection between the zone and a tremor was more certain, an "x" was placed in a column.

H. O. Wood (1916), influenced by the massive amount of information summarized by the California State Earthquake Commission after the 1906 San Francisco earthquake (Lawson *et al.*, 1908), attempted to correlate the larger historic earthquakes with major fault zones. Not knowing the existence of the Newport-Inglewood zone, Wood found it necessary to propose a hypothetical "San Pedro Submarine fault-zone" to be the locus for several southern California earthquakes. His reasoning was as follows (1916, p. 76):

> Certain shocks felt at points along the southern coast between the Santa Barbara region and the San Diego region seem surely to have been generated at sea. A submarine fault is known just east of San Clemente Island; but it is not warrantable to assign these shocks to this fault definitely, for it is too distant to be the probable source of them. Nor would the vague information recorded justify such assignments even if the fault were nearer the coast. However, no other submarine fault is known definitely off this shore. Consequently a vague term, the San Pedro Submarine fault-zone, is employed to designate a submarine generatrix whose location and extent cannot be delineated even approximately.

Whenever there was seismic activity associated with an earthquake assumed to have originated beneath the sea in the Los Angeles region, he felt that this "fault" was responsible (for example, July 10, 1855; August 10, 1879).

The following account includes descriptions of those larger earthquakes which Wood (1916) considered as having been generated most probably on the "San Pedro Submarine fault-zone":

1769, July 28. Los Angeles Region.

> When these shocks occurred these travelers [Portola and company] were in the vicinity of San Pedro Bay, on some old maps called Bahia de Los Temblores. A movement on almost any of the faults of the southern part of the Coast Mountains province *might* have produced such a disturbance; but one or more of the following taken in order of probable importance, seems the more likely source: the San Pedro Submarine fault-zone; the San Jacinto fault; the San Gabriel fault; or the Elsinore fault. The Whittier fault, the Santa Ana fault and the Santa Monica fault are very unlikely possibilities.

1812, September, October, or December(?). Coast Region of Southern California.

> Serious damage to buildings and loss of life at San Juan Capistrano, and at Santa Ynez . . . a seismic sea wave at Refugio . . . a multitude of aftershocks, with continuous vibration of the ground at Santa Barbara for eight days.
>
> As a speculation merely, it is interesting to note that the phenomena could best be accounted for as the result of two, or more, strong shocks—one generated either on the north end of the San Pedro Submarine fault-zone, the Santa Ynez fault or the San Gabriel fault,

wreaking havoc at Santa Ynez, Refugio, San Fernando and San Gabriel; the other caused by movement on the south end of the San Pedro Submarine fault-zone, the San Jacinto fault, the Elsinore fault or the Santa Ana fault, causing destruction at San Juan Capistrano.

1855, July 10. Los Angeles-San Gabriel.

Four shocks in twelve seconds. Two unusually heavy sea waves at Point San Juan [most likely Dana Point; not Avila as reported in Hamilton *et al.*, 1969, p. 53]. Bells thrown down in the San Gabriel Mission church.

Seismic sea-waves are considered to indicate submarine disturbance; hence the vague San Pedro Submarine fault-zone is taken as the most probable origin. Possibly the San Gabriel or Elsinore fault suffered disturbance also.

1879, August 10. San Fernando-Santa Monica.

Tidal wave at Santa Monica.

On account of the sea-wave it seems most probable that this shock was generated on the San Pedro Submarine zone; if not then it is likely that its focus lay in either the San Gabriel or the Santa Monica fault.

As is mentioned in the section on the early history of the investigation of the zone (page 30), Homer Hamlin seems to have been the first to associate earthquakes with the Newport-Inglewood zone. Hamlin (1918) reported that 20 earthquakes occurred in 1917 along the Newport-Inglewood zone (see table 4). According to Taber (1920, p. 143), Hamlin thought that the epicenters for the 1917 earthquakes (see quotation on page 30) were located along the northeast side of the hills of the uplift. Taber also noted that Arnold "suggested that the more unconsolidated character of the soils on that [east] side of the ridge may have locally accentuated the apparent intensity of the shocks and thus influenced Hamlin to locate the epicenters too far toward the northeast" (1920, p. 143).

Taber (1920, p. 143) believed the 1920 Inglewood earthquake was centered west of Inglewood. Kew (1923, p. 158), on the other hand, suggested that "the greater amount of damage caused by the 1920 shock on the west side of Inglewood may have been due to the fact that this area is underlain by loosely consolidated sands and gravels of Pleistocene age. These would have a tendency to settle more readily and cause greater damage to property than the more thoroughly consolidated material composing the rocks east of the Inglewood fault."

The Inglewood earthquake of June 21, 1920, was the first earthquake associated with the zone to receive any detailed field study. This earthquake also stimulated active interest in the seismicity of the zone. An example of this interest is the topic of the September 3, 1920, meeting of the American Institute of Mining and Metallurgical Engineers held in Los Angeles. A number of talks were presented on "The Earthquake Problem in Southern California" (Bulletin of the Seismological Society of America, 1920, v. 10, p. 276-299). It should be pointed out that, in addition to the Inglewood earthquake of June 21, 1920, there also occurred on July 16 tremors which were centered in the vicinity of downtown Los Angeles. At the meeting referred to above, William Mulholland (Chief Engineer of the Los Angeles aqueduct) spoke of his experiences in the Inglewood area both as a resident and as an engineer. Apparently, some of his comments contain the only known record of certain smaller shocks felt locally along the northern end of the Newport-Inglewood zone. Mulholland (1920, p. 289-297) included several interesting points about construction along the zone and the seismic history of the region:

I have known for many years the existence of a fault or fold of the crust there [vicinity of Inglewood], that we used to call, in the early days, the Rosecrans Ridge, though it lost its identity by that name in later years. Along that hill or ridge the first earthquake I experienced

in California occurred, right at Inglewood. That was 1878. It was a shock similar to that which was felt there quite recently June 21, 1920. Since then, to my knowledge, there have been four similar shocks, of about equal intensity, almost at the same spot, sometimes felt farther along to the southeast, down towards Cerritos, but always more intensified in the region of Inglewood than anywhere else along the ridge.

The geological structure of that ridge is well known to most of the engineers who have to do with water development. Homer Hamlin drove a tunnel through it for the outfall sewer, and in driving it be [sic] passed through the Pleistocene beds of gravel, where the ridge has its least development and elevation, in the neighborhood of Inglewood.

A little to the southwest of where that ridge has its lowest development, there is a large tank constructed by the Water Department two years ago. When I constructed that tank, I knew the seismological character of the country, and I kept telling my young engineer assistants that it would be the most vulnerable part of the Los Angeles Water Works.

In my early experience, I made a great many borings for wells along the ridge at Rosecrans Hill, and I found out that the top of the formation was Pleistocene, and the ridge had a level in common with the coastal plain. When I built the tank, I had to have some sand to make the foundation. In the excavations there [where the tank is], I found the sands of the Pleistocene, sands and gravels; and I found, very curiously, in those beds of sand, jogs and offsets, with silt streaks in the formation of the beds, with, in some places, a vertical offset of a foot or two, showing that since it has risen from the level of the surrounding coastal plain there has been movement of slicing and shearing in the hill itself.

The 1878 shock listed in table 4 comes from the above comments. It is not known when the other shocks occurred, but some may have been the 1917 earthquakes mentioned by Hamlin.

Inglewood Earthquake, 1920

The literature directly related to the Inglewood earthquake of June 21, 1920, is limited to four articles (Arnold, 1920; Taber, 1920, 1924; and Kew, 1923). Much of Arnold's short article is quoted earlier (page31). The only detailed report on the earthquake itself was written by Taber (1920), who was commissioned by the Seismological Society of America to make the investigation. A summary of the details is presented in table 5, compiled from Taber's article. Taber (1920, p. 129-132) reviewed and illustrated some of the destructive effects of the earthquake. A more specific account of damaged buildings and their locations can be found in Rosenberg's (1938) *History of Inglewood*. There were few multi-story buildings in Inglewood at the time. Most of the larger buildings were located in the vicinity of the City Hall along Commercial Street (now called La Brea Avenue) where much of the more spectacular damage was sustained. It is probable that Taber's conclusion (1920, p. 129) that "damage to buildings was due to poor construction rather than to the intensity of the vibrations" is the correct one judging from the descriptions of both the kinds of damage and the type of construction.

Table 5. Summary of data on Inglewood earthquake of June 21, 1920.

Time	6:47 p.m. Pacific Coast standard time (local time).
Magnitude	"Near 4.9" (estimated by Richter, 1970b).
Place	Most destructive in the immediate vicinity of Inglewood.
Area affected	11,000 square miles.
Intensity	8½ Rossi-Forel scale; "very strong shock".
Duration	Up to about 30 seconds.
Type of motion	Up and down, practically no lateral movement.
Epicenter	"Short distance west of Inglewood" (±1 mile) (Taber, 1920).
Depth of focus	Probably close to the surface (Taber, 1920, p. 145).
Surface faulting	No "evidence" of surface displacement found by Taber (1920).
Foreshocks	June 18; 2:08 a.m.
	June 18? or 19?; 10:30 a.m. 1¼ miles west of Inglewood.
	June 21; around noon, 2 light shocks, Inglewood Cemetery.
	June 21; 2:08 p.m. recorded on voltmeter at Sawtelle Soldiers' Home.
Aftershocks	Many, mostly in the immediate vicinity of Inglewood.
	List of 36 aftershocks between June 21 and July 16, 1920, given by Taber (1920).

During his investigation of the Inglewood earthquake, Taber learned that a recording voltmeter located at the Soldier's Home (Veteran's Administration) in Sawtelle (West Los Angeles) had preserved a record of numerous "foreshocks" to the June 21 earthquake. The device simulated a seismograph and, although its records indicate that between February and June 21, 1920, at least 40 minor shocks occurred, not all were considered to be "foreshocks." Only four or five true foreshocks probably occurred (see table 5) according to Taber (1920, p. 132).

Taber (1920, p. 136) presented a list of numerous aftershocks. It is possible that many, if not all, of those shocks, which occurred after June 29, were associated with other fault zones, such as the one responsible for the July 16 earthquakes centered near downtown Los Angeles.

Neither Taber nor the others who investigated the effects of the earthquake could find any evidence of surface displacements along the faults that they were able to recognize. Taber (1920, p. 137) speculated, "The strong vertical vibrations which characterized the earthquake in the epicentral region, indicate that the recent displacement was probably vertical or nearly vertical."

Earthquake History, 1920 to 1933

During the interval between the Inglewood and Long Beach earthquakes, the expanding population and growing awareness of seismicity of the Los Angeles area resulted in an increase in the number of earthquakes reported compared to the period prior to 1920. Data for pre-1928 earthquakes felt in the Los Angeles area and not specifically known to have occurred on other fault zones are listed in table 4.

Beginning in 1928, the U.S. Coast and Geodetic Survey published yearly summaries of seismic activity entitled "United States Earthquakes." Table 6, which was prepared from these summaries and from "Seismological Notes" which apppear in the Bulletin of the Seismological Society of America, lists local earthquakes which might have originated along the Newport-Inglewood structural zone.

Table 6 shows that, although minor seismic activity was common for the interval represented, there does not appear to be any specific forewarning of the destructive Long Beach earthquake of March 10, 1933, with the exception of the March 9, 1933, Huntington Beach shock. Of course, the latter shock was later recognized as a foreshock of the major event.

Long Beach Earthquake, 1933

The Long Beach earthquake of March 10, 1933, represents the most dramatic example of the consequences of disregard or ignorance of the seismic hazards associated with the Newport-Inglewood structural zone. Fortunately, many of the lessons learned about the response of certain types of structures to a seismic event from the 1933 earthquake resulted in the formulation of building codes and regulation of building practices. The California legislature, in response to the damage caused by the Long Beach earthquake, rapidly passed the Field Act, under which the construction of public school buildings is regulated, and the Riley Act, which regulates all other building for human occupancy other than two-family dwellings or less. That an earthquake of relatively low energy (magnitude 6.3) should have caused so much damage

Table 6. Post-1920 (Inglewood), pre-1933 (Long Beach) earthquakes.

Date	*Locality data*	*Intensity**	*Origin possible/ probable on Newport-Inglewood zone*
1928 Jan. 7	Santa Monica; shook crockery, no damage	II–III	X
1928 Nov. 18	Redondo Beach; 2 shocks from west	III	
1928 Nov. 27	Los Angeles; shook windows	III	
1928 Dec. 31	Near Torrance; reported from Santa Monica, Long Beach, and other beach towns to Los Angeles		X
1929 Oct. 31	In San Pedro Channel (Wood); strong in hill section of San Pedro and Wilmington; slight at Long Beach, Avalon, Redondo, and Los Angeles		
1930 Aug. 30	Near Santa Monica; 33° 57′ N, 118° 38′ W, at Los Angeles and towns surrounding Santa Monica Bay, 11,500 square miles affected; 5.2 magnitude	VII–VIII	X
1930 Aug. 31	Six aftershocks of August 30 shock		
1930 Sept. 30	Culver City	"fairly strong"	?
1931 April 24	In San Pedro Channel near Los Angeles; 33° 46′ N, 118° 29′ W; felt over 3,000 square miles on land	V	
1931 July 13	Huntington Beach	"slight"	X
1931 July 27	Huntington Beach	"feeble"	X
1931 Aug. 5	San Pedro Channel		
1931 Aug. 13	3 miles east of Torrance near Lomita	"feeble"	?
1931 Aug. 14	Torrance (same as above)		?
1931 Aug. 30	Huntington Beach, center in San Pedro Channel according to Pasadena	"feeble"	X
1931 Nov. 1	Bell	"feeble"	X
1931 Nov. 3	Los Angeles region, T. 4 S., R. 14 W., near Hawthorne; 3 miles east of Torrance, Compton, Inglewood, Redondo Beach, South Gate	IV–V	X
1931 Nov. 4	Watts, Compton, Torrance; 3 miles east of Torrance	"slight"	
1932 Jan. 25	Wilmington 118° 17′ W, 33° 54′ N	"light"	X
1932 Jan. 31	Hynes, Long Beach, Wilmington, and near Torrance 33° 53′ N, 118° 19′ N	"weak"	X
1932 Feb. 10	Wilmington, 33° 54′ N, 118° 17′ W	"slight"	X
1932 March 21	Los Angeles region, 33° 54′ N, 118° 17′ W, Lawndale, Inglewood, Los Angeles, Manhattan Beach	IV	X
1932 May 15	Near Torrance, 33° 48′ N, 118° 14′ W		X
1932 July 30	Bell and Los Angeles 33° 55′ N, 118° 10′ W	"weak"	X
1932 Aug. 26	Huntington Park	IV	
1932 Oct. 21	Los Angeles and vicinity, Hollywood, Lennox, Long Beach, San Pedro, 33.7° N, 118.3° W	IV	X
1932 Nov. 3	Los Angeles County T. 4 S., R. 14 W., Torrance vicinity		
1932 Nov. 29	Huntington Park	III	
1932 Dec. 6	Huntington Beach (5 miles north of); blast?	IV	?
1932 Dec. 22	Huntington Beach	"slight"	X
1933 Jan. 26	Gardena and Lomita	III	
1933 March 9	Huntington Beach	IV	X

* Rossi-Forel scale to 1931—Modified Mercalli post-1930.

Table 7. Long Beach earthquake of March 10, 1933.

Time	5:54:08 p.m. PST at origin (California Institute of Technology, Pasadena).
Magnitude	6.3 on Richter magnitude scale—a "moderate" earthquake.
Area affected	Intensity VII felt over 450 square miles; earthquake felt over 10 southern California counties (100,000 square miles).
Intensity	Upper range of grade VII to VIII of the Modified Mercalli intensity scale of 1931; few isolated spots on worst ground reached IX.
Duration of main shock	"Hard shaking" from 5 to 15 seconds depending on locality of observer.
Epicenter	33° 34.5′ N latitude; 117° 59′ W longitude; approximately 3.5 miles offshore from Newport Beach, California.
Depth of focus	6 miles (10 km) depth subsea off Newport Beach but named Long Beach earthquake because of extensive damage there.
Surface faulting	"No fault displacement was found at the surface anywhere" according to H. O. Wood (1933). No seismic sea waves were observed.
Foreshock	March 9, 1933; 1:33 a.m. PST, near Huntington Beach, magnitude 4.
Aftershocks	Hundreds recorded; 78 aftershocks had Richter magnitudes 3.9 or greater.

and held such potential for loss of life and injury is not a geologic problem, but a cultural and an engineering one. A review of this event is thus useful to illustrate what can happen to the region in the vicinity of the Newport-Inglewood structural zone.

Most of the literature dealing with this event dwells upon the damage (both value of property lost and human losses) and the extent of destruction suffered at various localities. It is neither practical nor desirable to repeat, within the text of this report, all of the descriptions of damaging effects of the event which were written by numerous investigators directly after the earthquake. The best summary of all data pertaining to the effects of the Long Beach earthquake was assembled by Binder (1952). A bibliography of mostly nongeological references, which is derived primarily from the extensive one compiled by Binder, is given in Appendix A. According to Hillis (1958, p. 96) in the *Bibliography of Engineering Seismology,* "Mr. R. W. Binder of Los Angeles made a most thorough and painstaking compilation of data relating to the effects of this earthquake, and assembled the material into five large volumes. The data are summarized in Mr. Binder's paper presented at the Symposium [Earthquake and Blast Effects on Structures] in Los Angeles in 1952, but the complete material is available only in Mr. Binder's private files."

Articles which deal with the various seismological and geological features of the Long Beach earthquake are much less common than those which describe the destructive effects of the earthquake. Table 7 summarizes the important features of the Long Beach earthquake. An annotated bibliography of works dealing with the geology and seismology of the earthquake is given in Appendix B. The data presented in table 7 are taken mostly from Wood (1933) and Richter (1958).

CHARACTERISTICS OF THE LONG BEACH EARTHQUAKE

Epicenter. As reported by H. O. Wood (1933, p. 46) the "epicenter...is situated about five and one-half kilometers (3 1/2 miles) southwest of Newport Beach, *in the general course of a fault zone, commonly called the Inglewood fault, projected to the southeastward beyond its intersection with the coast line*" [italics supplied]. Wood felt that some explanation of the method of determining the epicenter was necessary because of the greater damage at places distant from the instrumentally determined epicenter. His discussion accounts for arrival times of first motion shock waves at the various seismograph stations in southern California and the drafting of intersecting hyperbolas which show the differences in distances to various seismographs. Wood pointed out (1933, p. 48) that "the point taken as the epicenter, 33° 34.5' north latitude, 117° 59' west longitude, is near the center of the small area" (circle of 5 km radius) indicated by these intersections.

Early news reports on the earthquake contained much misinformation but also exemplify the initial feelings of those who experienced it, uninfluenced by formal announcements from the Seismological Laboratory in Pasadena. For instance, a report printed in Engineering News-Record (March 16, 1933, p. 355) made the statement that,

> Although most reports state the belief that the quake was caused by movements along the San Pedro fault zone off the coast of Long Beach, Dr. Beno Gutenberg, of the California Institute of Technology, is said to have told the Associated Press that the Inglewood faults, starting in the Baldwin Hills north of Inglewood and running southward nearly to San Diego, were responsible.

The "official report" on the event, entitled "Earthquake Hazard and Earthquake Protection," which was prepared by the Joint Technical Committee on Earthquake Protection (Millikan, 1933), states that the Long Beach earthquake had "its origin beneath the sea about four miles southwest of Newport Beach and it was caused by slip on a submarine fault, *presumably on a fracture along the southern extension of the Inglewood fault zone*" [italics supplied]. J. P. Buwalda (1933), who was a member of the committee, gave a talk before the American Society of Mechanical Engineers at Los Angeles, on April 12, 1933, where he said, "The movement on the fault which caused the Long Beach earthquake took place under the ocean about 3 miles offshore, and hence cannot be examined directly; but it is traceable in its extension northwestward throughout the Los Angeles district, where it is known as the Inglewood fault, which was active in that suburb in the earthquake of 1920."

Although the location of the initial epicenter does not provide unambiguous evidence for involvement of the Newport-Inglewood structural zone, the locations of the epicenters of numerous aftershocks do indicate that the initial shock was most likely due to movements on the zone. Eaton (1933, p. 737) stated that Gutenberg informed him "that tentative figures indicate that the epicenters of the Long Beach earthquake aftershocks varied from 5 to 10 miles along the strike of the shear zone." Later, Benioff (1938) presented a detailed discussion of the extent of faulting at depth associated with the Long Beach earthquake. Benioff (1938, p. 77) stated that the "epicenter which Gutenberg and Wood located a few kilometers off the coast of Newport was determined by the arrival times of the first longitudinal waves. It therefore indicates solely the point at which faulting originated. It offers no information on the extent of faulting nor on the area from which maximum destructive energy radiated."

Furthermore, after comparing the seismograms from the initial shock with those from the aftershocks, Benioff concluded (1938, p. 77):

> It was clear . . . that the principal shock exhibited much longer periods than those of the aftershocks. This effect indicates that in the principal shock the fault displacement either took place more slowly or extended an appreciably greater distance. Since the first alternative makes the power of the principal shock less than that of the aftershocks, it must be assumed that fault extension is the cause of the longer periods.

Benioff outlined the procedure by which the extent of faulting can be determined by an instrumental method based upon the elastic rebound theory and the seemingly contradictory observation that transverse (S) waves may arrive at the seismograph before longitudinal (P) waves, even though P waves travel faster. Applying his simple formula to Wood's and Richter's travel-time data, Benioff concluded that faulting during the Long Beach earthquake extended from off Newport Beach to the vicinity of Signal Hill, a distance of 27 km (17 miles) at a velocity of approximately 4.2 km/sec. (see figure 11). As supporting evidence for this conclusion, Benioff noted (1938, p. 81) that Wood and Richter have shown that the aftershocks during the first few hours following the principal shock were almost uniformly distributed throughout the length of the segment indicated in figure 11.

Clements (1933) disagreed with the conclusion reached by seismologists on the location of the epicenter of the Long Beach earthquake. He attempted to apply Mallet's procedure (Richter, 1958, p. 33) in measuring the direction of fall of monuments in cemeteries in the Long Beach-Compton area. He inferred that the epicenter of the earthquake lay near Compton because there was "a marked convergence on the Compton area...with over 60 percent of the columns having fallen along lines radiating from Compton as a center" (1933, p. 101).

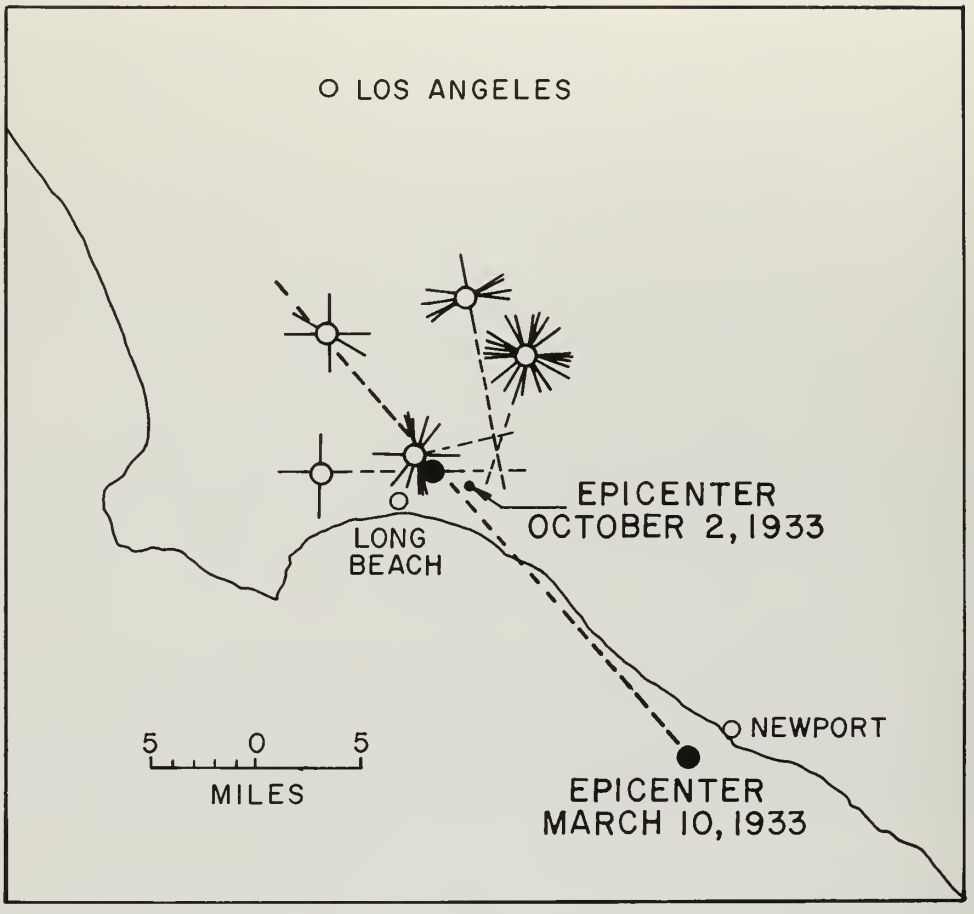


Figure 11. Graphic representation of Clements' data on fall of tombstones during Long Beach earthquake. Large filled circles represent ends of fault segment along which faulting is inferred to have occurred at depth during the Long Beach earthquake. (From Benioff, 1938, p. 82, fig. 5).

Benioff (1938) and Richter (1958, p. 34) later commented that Clements concluded Compton was the epicentral locality because he assumed that cemetery stones were overthrown by longitudinal rather than transverse waves. "It is common experience, however, that the transverse waves of earthquakes exhibit larger amplitudes than the longitudinal waves. It is to be expected, therefore, that transverse waves cause the larger number of falls" (Benioff, 1938, p. 82). When Benioff plotted Clements' data (see figure 11) on the assumption that the transverse waves caused the falls, he was able to show that the perpendiculars to these directions coverged on the epicentral locality determined by seismologists to lie offshore from Newport.

The intensive damage in the vicinity of Compton, according to Gordon Oakeshott (written communication, 1971) was "due to the fact that Compton lies in a basin, partly undrained except during floods, at and near sea level, with a very high water table in 1933. In fact, artesian water was obtained up to only a few years before that. The water-saturated alluvium caused damage to center in Compton. I was teaching there at the time of the earthquake, felt and heard the approaching P-wave and saw the damage. Some of the streets and curbs in central Compton were so fractured and displaced as to endanger traffic. At the College, my previously set benchmarks on the curb were displaced as to become unusable."

Although the distribution of the most heavily damaged structures is probably controlled by the type of ground (Gutenberg, 1957)—as well as by the general quality of construction (Martel, 1936; Binder, 1952)—the reaction of particular structures to the shock waves may indicate the direction in which the transverse waves traveled. Interpretation of such data often results in conclusions yielding ambiguous source directions. However, to show that the above directional data collected by Clements may not give a simple picture of the source direction, the following passage is quoted from Green (1933, p. 562):

> It seems reasonably certain, however, that in Long Beach that part of the motion having a magnitude and frequency of acceleration (which gave a destructive combination for most buildings) was in general a N- and S- direction. The cracks and spalling in the columns of the California Garage all showed a destructive flexure in this direction, as did also the cracks in the columns of the Ambassador Apartments. In the Professional Building the north and south first story partitions were heavily x-cracked, but those running east and west were undamaged. The front wall of the Long Beach Polytechnic High School and the rear wall of the Board of Education Building each face west and were obviously parallel to the direction of the destructive shock. In the case of the last named building the side walls were practically uninjured.

The 1933 Long Beach earthquake was one of the first larger shocks to be well recorded by nearby instruments (Heck, 1933; Heck and Neumann, 1933). Richter pointed out (1958, p. 497-498) that "epicenters for immediately following aftershocks were scattered along the Inglewood fault zone into the city limits of Long Beach, near the Signal Hill oil field." There is no reason to doubt his word that:

> Epicenter determinations are fairly reliable, especially in terms of relative position for different shocks of the series. The active area was surrounded on three sides by stations of the southern California seismological network, and data were supplemented by those of a portable instrument operated successively near Laguna Beach, Huntington Beach, Santa Monica, and elsewhere, including one short run on Santa Catalina Island.

Focus. One of the problems posed by the location of the epicenter 3 1/2 miles offshore near Newport is that this point is also that far from the traces of the known near-surface faults that define the Newport-Inglewood structural zone. Wood (1933, p. 46) stated that the depth of origin is less certainly known than the epicenter but that "both instrumental and field evidence point to a value shallower than usual, probably about ten kilometers (6+ miles). Should more prolonged study necessitate changes in the position and depth of the origin as given here, the amount of any such correction will be very small."

Wood appeared to be quite confident about the focal-depth determination. However, as Richter (1958, p. 315) pointed out, "The depth of hypocenters is of great geological and geophysical interest, but accuracy in determination is rare." Furthermore, "the geologist should be particularly wary of using local-earthquake epicenters and depths to determine such details as the dip of important faults, unless special seismological investigation appears to justify the procedure."

Foreshocks. Wood (1933, p. 43) noted that "for several years previously, sporadic shocks, some strong enough to be felt over very small districts, had been registered from sources located at various small distances to the northwest of the origin of the shock on March 10, 1933, most of these in a small region some sixteen to forty-eight kilometers (10 to 30 miles) distant." See table 6 for a listing of the perceptible shocks.

Discussing the Long Beach earthquake, Richter noted (1958, p. 67) with respect to the "Inglewood fault" that

> ...small recorded earthquakes from 1927 on were attributed to it. During 1932 there was a slight general increase in activity over much of southern California. So many small shocks were felt at Huntington Beach, near the Inglewood fault, that Mr. Martin Murray of that city set up a homemade seismograph to record them. After a major earthquake in Nevada on December 20, 1932, the general activity declined...On March 9 at 1:13 A.M. a true foreshock (magnitude 4) was sharply felt at Huntington Beach...The epicenter of the foreshock was not over a few miles from that of the main earthquake.

Although foreshocks have occurred prior to the larger (1920 and 1933) earthquakes associated with the Newport-Inglewood zone, they do not provide any basis for prediction of a large earthquake. This has been emphasized by Richter (1958, p. 67): "foreshocks seldom afford an opportunity for warning or prediction of major earthquakes, since there is nothing to distinguish foreshocks from ordinary small shocks." Nothing demonstrates this better than the lists of small tremors (table 6) that were not followed by large earthquakes.

Aftershocks. According to Wood (1933, p. 44) thousands of aftershocks were recorded following the major shock, "some of which were felt distinctly throughout the district affected, with some strong enough to cause alarm and do additional damage to structures already seriously injured [sic]." Wood tabulated many of the aftershocks which occurred between March 10 and 16, 1933.

The most important aspect of the aftershock activity, from a geological standpoint, is the means it provides for inferring the extent of faulting along the zone on which the major shock was centered (Benioff, 1938). The discussion of Benioff's methods and his conclusions appears on page 67. The portion of the zone supposedly involved in actual faulting (subsurface only) is indicated in figure 11.

Much more detailed information than is usually obtainable was derived from monitoring the local seismic activity following the Long Beach earthquake because the shock occurred so close to a seismological laboratory (Pasadena). Not only did the Long Beach earthquake serve as one of the initial examples used by Richter in his development of the magnitude scale (1935), but it also provided him with abundant data on aftershock activity and the energy release regime with respect to the major shock. This topic was further pursued by Benioff (1951) as well, with regard to both the Long Beach earthquake and the October 2, 1933, shock centered near Signal Hill.

According to Richter (1935, p. 31), from March 10 until the end of the month:

> ...there occurred more than seventy aftershocks of magnitude 4 and over, among which were at least six of magnitude 5 to 5.5. Even so, the total energy of these shocks was not a large fraction of that released in the main shock of magnitude 6 or over. Thus the conclusion is warranted that seismic energy is released principally in the larger shocks and their trains of aftershocks; while smaller shocks, occurring from time to time, do not appreciably contribute to the adjustment of regional strain, but are rather to be looked upon as minor symptoms of its existence.

Benioff (1951, p. 43-50) discussed in great detail the aftershock sequence following the Long Beach earthquake and concluded that the total wave energy released in the aftershocks (78 of which occurred between March 10 and May 16 with magnitudes of 3.9 to 5.2) amounted to only 12 percent of that released during the principal shock. Benioff (1951, p. 50) was quick to point out, however, that, although the energy released as seismic waves during the aftershock sequence equalled only a small percentage of that released by the principal shock, more than twice as much energy was

dissipated as heat during the first 20 days of aftershocks than was released as wave energy by the principal shock. Furthermore, because he concluded that the last destructive shock to occur prior to the Long Beach earthquake was that of December 8, 1812, Benioff (1951, p. 50) estimated that it took the intervening 120 years to accumulate the secular strain that was released by the Long Beach earthquake and its aftershock sequence in approximately 20 days.

An important consideration to be kept in mind when interpreting epicenter maps for all recorded shocks within a particular interval (for example, Allen *et al.* 1965, figure 7) involves the concept that all the small earthquakes felt in the vicinity of the zone (see table 6) over the years do not provide a basis for predictions of activity or quiescence along the zone. Richter (1935, p. 32) concluded from statistical studies of the frequency of shocks of various magnitudes:

> It is found that the seismic energy liberated in a given region during a given period is almost wholly accounted for by the larger shocks; the smaller shocks are not suffciently frequent to contribute more than a small fraction of this energy. It follows that the smaller shocks do not appreciably mitigate the strains which are released in the larger earthquakes, but must be regarded as minor incidents in and symptoms of the accumulation of such strains.

For a long time after the Long Beach earthquake, it was thought that the magnitude 5.4 earthquake of October 2, 1933, near Signal Hill represented an aftershock of the Long Beach earthquake (Benioff, 1938; Gutenberg, 1941; Richter, 1935), although there was uncertainty about this (Wood, 1934, p. 22).

According to Gutenberg (1941, p. 292), the seismographs that recorded both the March and October 1933 events were arranged in such a way that it is possible a superposition of horizontal and vertical movement records could lead to ambiguous interpretations about the actual movements at the epicenters. "Although a reversed movement along the fault is not excluded, the evidence is not good enough to favor such an explanation."

Later, Benioff showed (1951, p. 59-61) that the October 2 earthquake had its own train of characteristic aftershocks. The Signal Hill shock "occurred near or just beyond the northern limit of the epicenters of the Long Beach earthquake sequence. At the time of its occurrence there was an uncertainty concerning whether or not it was an aftershock of the Long Beach earthquake" (Benioff, 1951, p. 59). After showing that it does not fall on the appropriate strain-recovery curve for post-March 10 aftershocks, Benioff concluded that it is "safe to assume, therefore, that it was an independent event." Furthermore, Benioff noted that the aftershock sequence for the Signal Hill earthquake was observed for 136 days and possibly continued for a longer time.

In regard to aftershock activity, Richter (1958, p. 74-75) discussed the concepts that have been developed concerning the mechanisms responsible for earthquakes:

> A large earthquake is held to be due to the fracture of rocks under strain. The energy released in seismic waves and otherwise is held to be derived from the potential energy in the strained blocks as they snap back toward equilibrium--*elastic rebound*.

In reality, the situation is much more complex; Benioff (1951), according to Richter (1958, p. 75), developed the theory which considers complications of simple "elastic rebound" and takes into account "elastic afterworking" or "creep." As stated by Richter (1958, p. 75):

> Further motion will depend on the continuing tectonic forces which caused the original major strain; with lapse of time these may again raise the strain to the point of breaking

> through resistance. On the small scale, this may account for the sudden large apparent aftershocks, already noted, which occur after the general activity has subsided. On the large scale, this primary process determines the interval between major earthquakes on a given fault system.

Richter (1935, p. 30) assumed that the October 2 earthquake was a large aftershock of the Long Beach event and, therefore, felt that, because it was followed by such a long series of aftershocks, it did not represent a "return to equilibrium". Of the 67 shocks listed by Richter as occurring during the first four months of 1934 with magnitudes ranging from 1 to 4, 36 had a magnitude of 2.5. Richter (1935, p. 30) states:

> It is noteworthy that the Long Beach aftershocks definitely show an excess of shocks of magnitude 2 over those of magnitude 2.5; this is not true of the other lists, and probably arises, not from a larger proportion of small shocks, but from more positive identification and listing than for other earthquakes.

Richter emphasized that, because the total amount of energy released by even frequent small shocks is not equal to that released by the few larger shocks, the small shocks, therefore, cannot act to relieve accumulated strain. In other words, the frequency of small shocks along a fault zone is no guarantee that strain will not build up to be eventually released during an earthquake of larger magnitude.

With respect to aftershock activity, another item of interest was noted by Wood (1933, p. 48):

> One aftershock, on March 11th, was definitely determined by a party engaged in geophysical prospecting to have emanated from a source to the eastward from a group of field seismometers distributed over a limited area near Seal Beach. Though the position of the source of this shock was not fixed by these observations, its general direction from Seal Beach was determined absolutely without ambiguity.

Surface Effects. It is important to search for records of the effects produced in the ground surface, rocks, soils, or in the ground-water regime by the Long Beach earthquake because of the possible association of the effects to actual tectonic movements along various fault segments of the zone.

Numerous references to surface geologic effects of the Long Beach earthquake are listed in the abstracts of reports accumulated by Maher (1933) although there is no definite evidence for actual surface faulting. "No fresh movement of faulting extending to the surface has been observed anywhere on this occasion" (Wood, 1933, p. 53). Features noted include cracks in ground, settling effects in filled land, landslides, rockfalls, and others. These observations have been summarized in table 8.

Cracks appeared in alluvium at various places within the shaken region (see photos 14, 15, 16). Wood (1933, p. 53) stated:

> There are a few sparsely distributed cracks in the ground in the wet, alluviated bottom land of the Los Angeles plain, one or two of which exceed a kilometer (0.6 mile) in length. These are diverse in direction and appear to be, without doubt, simply secondary cracks in loose ground such as always result in shocks of destructive force and magnitude...To guard against misunderstanding, however, it should be stated that some of these cracks follow directions approximately parallel to the Inglewood fault zone, and other recognized faults, but it is clear that they do not mark, or follow, the surface outcrop of known or suspected faults.

One of these cracks was illustrated by Wood (1933, plate 5a) and Hillis (1933, p. 740). This particular crack had a N 45° W trend and was about 6 feet long and 5 feet deep. It was located in a field half a mile southwest of the intersection of Olive (now

called Alondra) and Atlantic Boulevards on the eastern side of Compton in the unconsolidated sands of the Los Angeles River flood plain. Hillis (1933, p. 740) postulated that the crack was created "after the passing of the compression wave [when] the unconsolidated sand, lacking elasticity, failed to return to its original position."

Table 8. Surface effects of the Long Beach earthquake (From U.S. Coast and Geodetic Survey Abstracts)

Locality	*Surface effects observed*	*Reference (in Maher, 1933)*
Anacapa Island	Two simultaneous landslides; larger one appeared to carry several hundred tons of material.	page 1
Long Beach	Cracked ground.	page 12
Newport Beach	Water mains leaked.	page 14
Piru	Several noticeable mountain slides.	page 15
Topanga	Rock fell into road.	page 19
Anaheim	Water in lily ponds in park down 2 feet, possibly as a result of large crack.	page 29
Bolsa Chica Gun Club	Crevices appeared in the fields and cracks in the highway, pavement displaced (see photos 11, 12, 13).	page 29
Garden Grove	Leaking water mains.	page 31
Huntington Beach	The 500-foot extension to the pier, constructed of steel and concrete, separated from the main section, a 2-foot crack resulting.	page 31
Laguna Beach	Water mains broken.	page 32
Long Beach	Water mains had broken; fire hydrants on Anaheim Street near Orange Avenue had broken; pavements displaced, roads cracked; abutments to bridges were damaged.	page 33
San Gabriel River Bridge	All traffic detoured on account of difference in elevation of bridge and approach.	page 35
San Pedro District	Numerous leaks in gas line; water mains broken; a crack a foot wide in the apron of the terminal at Berth 156–160, mud "volcanoes" at Cabrillo Beach.	page 36
Santa Monica	A few minor landslides occurred along the coast palisades.	page 36
Seal Beach	Mud "volcanoes" formed near the north end of Seal Beach (see photos 17 and 18).	page 37
Watts	Broken water mains.	page 38
Coast Highway	Damaged between Laguna and Newport Beach, in places, highway spread in center; in other places, one side dropped below grade, while in others, again, the cement pavement buckled.	page 38
Santa Ana River Bridge	At Fifth and Seventeenth Street—closed; culverts at both ends of bridge shifted; roadway near Santa Ana overflow bridge jacked up with mud.	page 38
Alameda Bridge	Sidewalks cracked and lifted near bridge; bridge beams displaced. Numerous small cracks appeared on the hill.	page 48
Long Beach (Belmont Shore)	Land in vicinity of filled-in canal settled and cracks appeared 2 to 4 inches wide, pavement buckled (see photos 19 and 20).	page 53
Coast Highway	Between Huntington Beach and Newport the three-lane highway was spread to about eight inches between each lane for about 150 feet at a place 2½ miles from Huntington Beach; the NE side lane had settled 15 inches below original level (photos 6 and 7).	page 56
Cliffs near Balboa Island Bridge	Tons of dirt slid down on the road from bluffs.	page 57

Photo 6. Damage to Pacific Coast Highway (1.4 miles southeast of Huntington Beach Pier) where the road had been built on fill across an old tidal slough (see page 78 for additional discussion of this damage). *Photo from Long Beach Public Library history collection; probably taken on March 11, 1933.*

Photo 7. Settling cracks along landward edge of damaged Pacific Coast Highway where it was built on fill across an old tidal slough 1.4 miles southeast of Huntington Beach Pier. Pacific Electric railroad trestle in background. *Photo from Long Beach Public Library history collection.*

Photo 8. Settling cracks between Pacific Coast Highway (see photo 7) and lagoonal ponds (now between Beach Boulevard and Newland Street) at the northwestern end of a zone of cracking which crossed the highway and passed under the Pacific Electric trestle (photos 9 and 10). *Photo by C. R. Browning through the courtesy of W. R. Moyle, Jr., U. S. Geological Survey, Garden Grove, California.*

Personnel of the California Department of Water Resources (1968, p. 38) in their study of sea-water intrusion in the Bolsa-Sunset area in Orange County noted that, although "the Newport-Inglewood fault does not displace the Recent land surface", the "Recent deposits have been affected by seismic activity" (see page 77). They quoted a letter by C.R. Browning, an engineer, as follows:

> Although the Long Beach earthquake is not known to have caused any vertical displacements, many cracks developed in the land surface along and near the structural zone, especially near Hog Island in the Sunset Gap and near the coast in Santa Ana Gap [see photos 8, 9, 10].

It is stated in California Department of Water Resources Bulletin 63-2 (1968, p. 13) that in Sunset Gap "Hog Island and another upper Pleistocene hillock which interrupt the Recent surface are small features, less than 400 feet across and 12 feet above sea level. They are probably remnants of a dissected scarp of the Newport-Inglewood fault."

Also appearing in California Department of Water Resources Bulletin 63-2 is a quotation from a letter by Penn Rowe, a geologist, who stated, "Mr. Browning also noted sand boils and flowing water along the fault trace in Santa Ana Gap following the 1933 earthquake" (1968 p. 38). Because of the marshy nature of the ground in Sunset, Bolsa, and Santa Ana Gaps at the time of the Long Beach earthquake, it would have been very difficult to decide unequivocally about the tectonic significance of the cracks observed there. By comparison with maps in Department of Water Resources Bulletin 147-1 (1966), the features photographed by Browning and reproduced as photos 8, 9, 10 do not correspond with any known fault or ground-water barrier in the sediments which fill Santa Ana Gap. Using aerial photographs taken in 1927, it is possible to locate accurately the site of the surface effects shown in the figures. These

Photo 9. View southeast along ground cracks which continue beneath Pacific Electric trestle (photo 10) 1.4 miles southeast of Huntington Beach Pier. Pacific Coast Highway on left. The line of cracking appears to correspond with settlement along the edge of a filled estuarine channel or old tidal slough which has been covered by dune sand and across which the trestle was built. *Photo by C. R. Browning through the courtesy of W. R. Moyle, Jr., U. S. Geological Survey, Garden Grove, California.*

Photo 10. Closer view southeast along ground cracks which continue beneath Pacific Electric trestle as shown in photo 9. *Photo by C. R. Browning through the courtesy of W. R. Moyle, Jr., U. S. Geological Survey, Garden Grove, California.*

particular cracks, at 1.4 miles southeast of the Huntington Beach Pier, developed along the edge of a filled tidal slough and can best be attributed to settling at the contact between differing underlying materials.

Recently, detailed investigations of the area about Sunset Gap and Bolsa Chica Mesa have been made by Bechtel Corporation (1967) in order to evaluate a proposed artificial island site for a nuclear-powered generating and desalting plant. Part of this study involved the application of subbottom profiling (Arcer-Sparker) techniques in an attempt to locate near-surface evidence of faulting. Of particular interest here are the traverses made along the channels of Huntington Harbour, a marina and residential development situated in a drained and modified portion of Sunset Bay between Seal Beach and Bolsa Chica Mesa. One traverse intersected the trace of the Seal Beach fault in one of the channels of the Huntington Harbour development. This intersection is a mile southeast of Hog Island and 1,500 feet southeast of the unnamed hillock mentioned above (which now forms part of one of the islands in the Huntington Harbour development). The Bechtel geologic staff and their consultants (Alpine Geophysical Associates) concluded (1967, p. 25) that, "even at the 400-foot depth in the Huntington Harbour crossing of the fault trace, the beds appear to have been more warped than displaced." This suggests that, whereas it might have appeared that surface faulting took place in the vicinity of Hog Island and in Sunset Bay as discussed above, actual surface faulting probably did not occur.

Photo 11. Slumped and cracked northeast-trending causeway across Bolsa Bay to Bolsa Chica Gun Club. View northeast toward Bolsa Chica Mesa. *Photo from Long Beach Public Library history collection.*

While on the subject of the near-surface effects of earthquakes in the vicinity of the gaps along coastal Orange County, it should be pointed out that personnel of the California Department of Water Resources, who observed and illustrated contorted structures in "Recent deposits exposed in vertical channel walls within 400 feet of the [Seal Beach] fault trace at Huntington Harbour" (1968, p. 38), concluded (p. 39) that the structures probably developed quickly "due to liquefaction of the loose sand and slumping of the silt resulting from seismic compression." This conclusion follows the

observation that the depositional environment in the lagoon must have been one of very low relief; therefore, it is unlikely that the features developed as a result of sedimentary processes or slumping.

To prevent misunderstanding, it should be emphasized that they did not say that these features formed during the Long Beach earthquake but that Holocene deposits in Sunset Gap, in the vicinity of the Seal Beach fault, display dramatically contorted structures that are best explained as forming during seismic activity along the fault. In addition, a very significant conclusion from their studies in Bolsa Gap is that there has been "little or no intrusion of salt water into the Recent Bolsa aquifer" northeastward of the Newport-Inglewood fault (1968, p. 9). This conclusion contrasts with the findings in the other gaps that Holocene deposits do not contain barriers to groundwater flow across faults of the Newport-Inglewood structural zone.

Photo 12. Settling cracks and slumped and caved shoulders along causeway to Bolsa Chica Gun Club. View southwest toward Pacific Coast Highway. *Photo from Long Beach Public Library history collection.*

Numerous accounts of the earthquake effects seen in roads and bridges are listed in table 8. Photographs of damaged pavement, cracked shoulders, etc., were published by Wood (1933, plates 5c, 6c, and 9c) and by Cortelyou (1933, photos 1 through 6). S.V. Cortelyou, who was the local District Engineer for the California Department of Public Works, described some of the effects in detail (1933). He pointed out that most of the damage to roadways was confined to the area along the coast between Long Beach and Newport Beach, especially where the coastal highway had been constructed over an old tidal slough or estuary (see photos 6, 7, 13):

> The whole surface of the ground within the area affected by the earthquake seems to have undergone a severe undulatory motion which left the pavement slightly rougher than before. Movements on adjoining strips of pavement did not always synchronize with the result that when the tremor was over, a depression would sometimes be left in one strip opposite a summit on the adjacent strip. (p. 2)

More specifically (p. 10):

> ...just southeast of Huntington Beach where spectacular damage occurred, there was a section of concrete pavement a few hundred feet in length, also located over an old estuary. Such violent undulations took place here that when the pavement finally came to rest after the temblor the outside 10'strip on the landward side at one place was found to be as much as 14"lower than the adjacent strip.

The greatest damage to any of the bridges affected by the earthquake was sustained by the Anaheim Bay Bridge near Seal Beach. Cortelyou (1933, p. 10) noted that the over-all length of the bridge was reduced about 9 inches and that the "shortening appears to have come practically all from the shifting of the south end of the bridge toward the north."

Gilluly and Grant (1949) discussed the elevation changes in the vicinity of Long Beach--both uplift and subsidence--that occurred in the interval between the 1931-1932 and the 1933-1934 leveling surveys. They noted (1949, p. 466) that "the Long Beach earthquake of March 10, 1933, took place in the interval between these surveys, and ground movement at the time of the quake ruptured pavements and displaced curbings at many points in the area" of Long Beach. They detected two types of changes in elevation--localized (less than 2 square miles affected) and regional (very much larger area)--and concluded that, while changes in single bench mark elevations could be due to local lurching, the regional changes must be tectonic in origin. The maximum uplift of 0.610 foot occurred at the junction of Palo Verde Avenue and Stearns Street (now the San Diego freeway) west of the San Gabriel River. The axis of the area of uplift parallels the Newport-Inglewood zone about 2 miles northeast of the Seal Beach and Signal Hill oil fields (figure 12). Gilluly (1949, p. 562) noted that this area had been bowed upward "presumably at the time of the quake--into a gentle arch about 7 inches high and 4 miles across. As the southerly part of the plain, nearer the epicenter, was not surveyed, the uplift there may have been greater...The changes in elevation are too systematic to be explained by lurching of surficial materials; the upwarping must indicate anticlinal folding at depth."

Photo 13. Settling cracks in shoulder of Pacific Coast Highway along Bolsa Bay looking northwest toward the junction with Warner Avenue (formerly Los Patos Avenue). *Photo by Olaf P. Jenkins.*

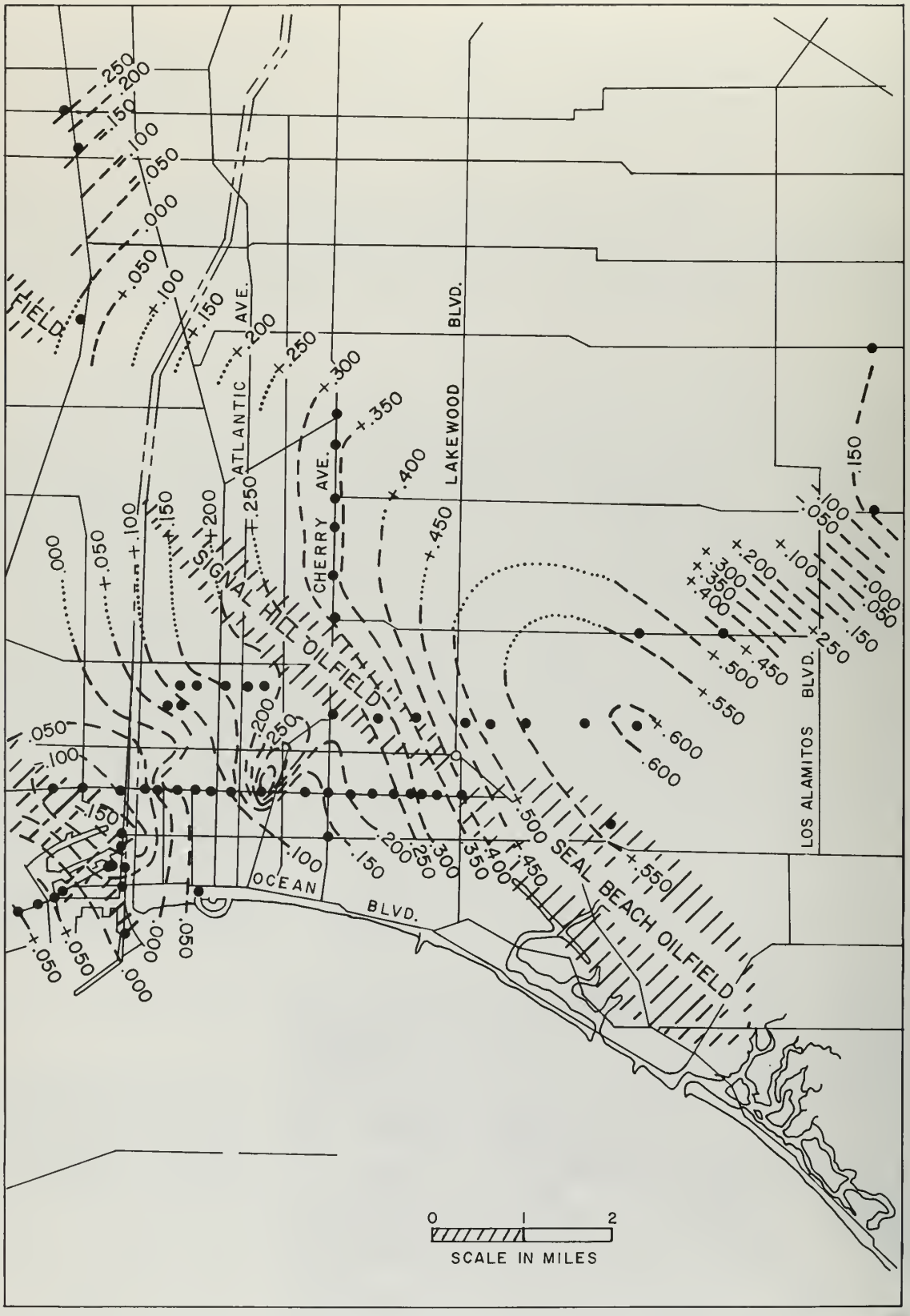


Figure 12. Uplift at Long Beach, California, shown by comparison of 1931 and 1933-34 releveling of U. S. Coast and Geodetic Survey precise levels. The Long Beach earthquake took place in the interval between the surveys. (From Gilluly, 1949, p. 563, fig. 1).

This uplifted area, defined by repeated leveling surveys, overlies the postulated buried boundary between the so-called eastern and western basement complexes as interpreted by Yerkes *et al.* (1965, p. A48) which, they inferred, "on the basis of gravity data,...is about 1.5 miles to the northeast" of the Cherry-Hill fault along Signal Hill. The area of maximum uplift also lies within a mile of the epicenter of the 5.4 magnitude, October 2, 1933, earthquake which was, according to Benioff (1951), not an aftershock of the Long Beach earthquake. It is possible that the uplift occurred during this shock and not during the March event. Of course, as Castle (1966, p. 28) pointed out, it is not known whether or not the uplift developed slowly or almost instantaneously during the earthquake.

Photo 14. Cracks in field west of Garden Grove, presumably from which sand and water was ejected during the earthquake. According to caption on original photo by C. R. Browning the crack was 1/2 mile long and was oriented approximately at right angles to the trend of the Newport-Inglewood zone. *Photo courtesy of W. R. Moyle, Jr., U. S. Geological Survey, Garden Grove, California.*

Photo 15. East-west to northwest-trending low, ridge-like feature (arrows) in San Gabriel River floodplain sediments northeast of Pacific Coast Highway bridge. *Photo by Olaf P. Jenkins.*

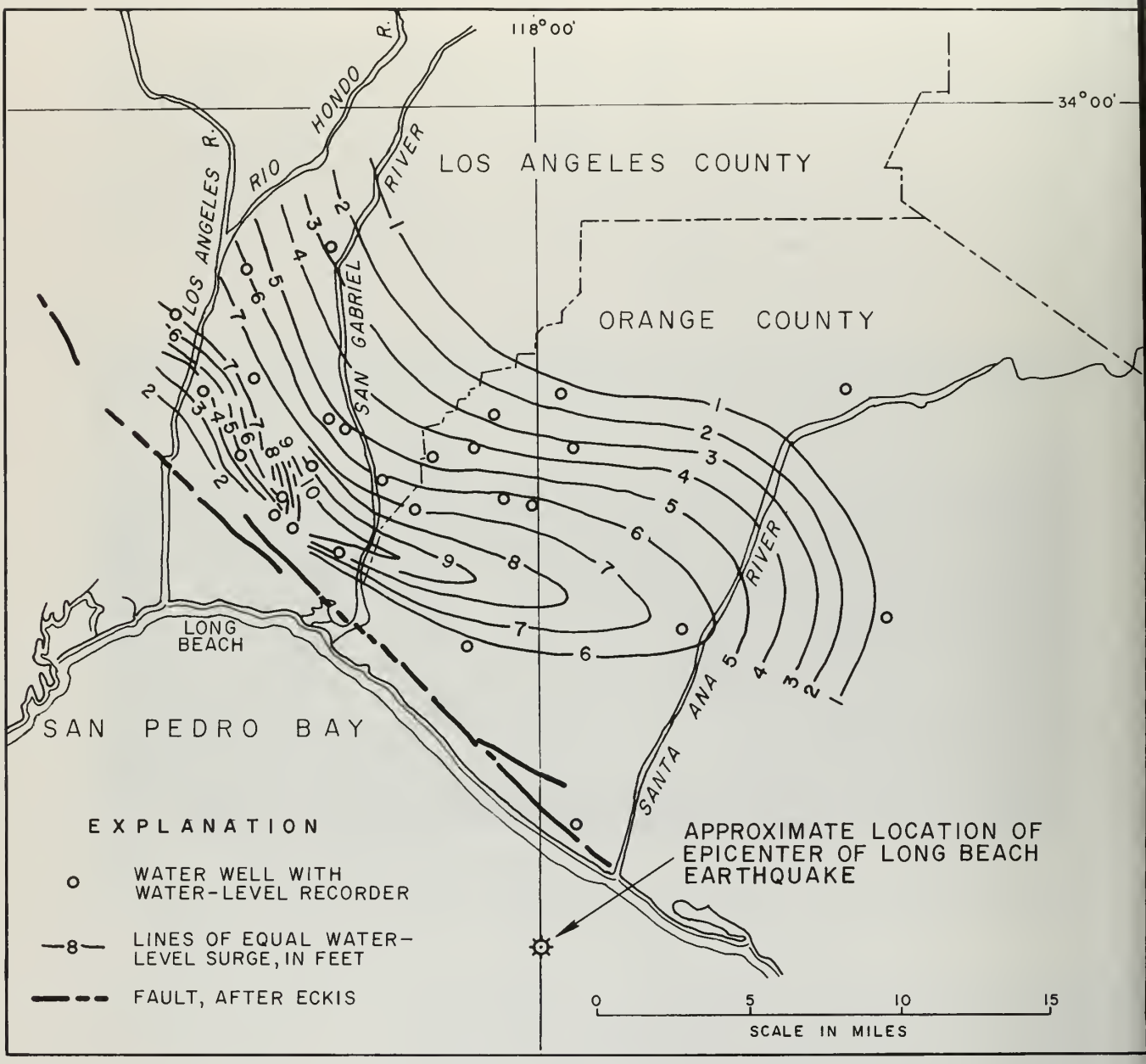


Figure 13. Sketch map of parts of Los Angeles and Orange Counties, California, showing lines of equal water-level surge in wells during the Long Beach earthquake. (From La Rocque, 1941, Transactions of the American Geophysical Union, v. 22, p. 379, fig. 4).

In discussing the cause of small, local changes in elevation Gilluly and Grant (1949, p. 492) referred to the phenomenon of lurching or the

> ...shaking of more or less incoherent superficial sediments such as damp or saturated alluvial bottom lands as a result of the passage of surface earthquake waves...The Long Beach earthquake...produced some conspicuous lurches in bottom lands. The horizontal displacements in the Alamitos Bay section of Long Beach...probably were due to lurching during this earthquake...The irregular distribution, both in sign and amount of movement, between the surveys of 1931-1932 and 1933-1934 strongly suggests local differences in the response of the surficial material to the strong ground waves at the time of the Long Beach earthquake.

Changes in the ground-water regime and in the level of the water table in wells were also closely connected with the settling of the unconsolidated material typical of

much of the region affected by the Long Beach earthquake. La Rocque (1941) demonstrated the relation between earthquakes and water-level surges in wells in the Los Angeles basin. At the time of the Long Beach earthquake water-level recorders were operating in 26 wells which ranged in depth from 81 to 1,570 feet.

A map of the region (figure 13), on which are plotted water-level surges recorded at the time of the earthquake, shows that "(1) The greatest known water-level surge in wells during the Long Beach earthquake occurred just northeast of and close to the so-called Inglewood-Newport fault-zone close to Signal Hill but (2) the epicenter of the earthquake was apparently some 15 miles to the southeast, about on the prolongation of the fault-zone and a few miles offshore" (La Rocque, 1941, p. 385).

Photo 16. Lurch crack in alluvium near Alamitos Bay. *Photo by W. W. Bradley.*

In addition to the almost instantaneous rise in the water level in the wells (a surge), there also occurred "a residual or semi-permanent rise in water level in 24 of 25 wells; this residual rise was from 0.019 foot to 8.23 feet" (La Rocque, 1941, p. 379).

Noting that in the vicinity of the greatest water-level surge the impervious beds in the unconsolidated deposits are thickest, La Rocque suggested (1941, p. 385) that the amount of surge was controlled by the thickness, perviousness, and elasticity of the water-bearing zones, as well as by the effectiveness of the confining beds. The effect of the earthquake on the water levels in wells provides an indirect method for inferring the configuration of the subsurface units. The trend of the contours of the water-level surge (figure 13) was apparently controlled by the trend of the fault zone. La Rocque postulated (1941, p. 385) that the "fault-zone locally resolved the forces set up in the bed-rock by the Long Beach earthquake and determined to a very considerable degree the direction and magnitude in which those forces were imparted to the over-lying unconsolidated deposits."

There is a similarity between effects observed in water-table levels and effects observed on the land surface (mud craters, sand boils, seepage, etc.) in areas underlain by water-saturated unconsolidated materials. Both these features are related to the deformation of the sediments and accompanying reduction of pore space which results in movement of ground water. That movements on faults which extend almost to or to the surface (Cherry-Hill, Seal Beach, and related faults) did not occur, thereby causing the

effects observed in the ground water regime, is demonstrated by evidence from oil wells that are located closer to and penetrate deeper into these fault zones. In reference to the effects due to aftershocks of the Long Beach earthquake, Eaton reported (1933, p. 738):

> The unexpectedly small damage to oil wells along the shear zone, most of which are a mile or more deep and lie almost astride of the epicenter, indicate that the secondary surface fractures which pass by, between, and through these wells did not move appreciably.

Other effects related to near-surface movement of ground water were noted by Wood (1933, p. 54). Water was ejected from cracks, especially in the flood plain deposits between Newport Beach and Huntington Beach and in the vicinity of Compton. This occurred not only in "areas of water-soaked ground" but also "in some places where the ground is not obviously heavily charged with water."

Photo 17. Settling and slumping o shoulder along what is now Marin Drive in Seal Beach. Note mud crate in mudfilled ditch along road. *Photo b Olaf P. Jenkins.*

Photo 18. Close-up of mud crater in ditch along Marina Drive shown in photo 17. Water was ejected from the mud at this locality during the earthquake. *Photo by W. W. Bradley.*

Wood also reported (1933, p. 54) that the flow of wells and springs exhibited changes after the quake. Most of the wells had increased flow temporarily, and in some the water stood at a higher level as described above. There was also a notable increase observed in the temperature of springs and ejected water in many cases.

An important effect to record for earthquakes with sub-sea origins is the activity of the sea water. Wood (1933, p. 55) said, "There are no reliable reports of any conspicuous disturbance of the sea." More specifically, although the tide-gauge record for March 10, 1933, shows the actual movement of the shock, there is no record of a

Photo 19. Failure of land fill behind slumped sea wall at Naples district of Long Beach. *Photo from Long Beach Public Library history collection.*

Photo 20. Disrupted curbing and pavement along the Toledo in the Naples district of Long Beach. *Photo by Olaf P. Jenkins.*

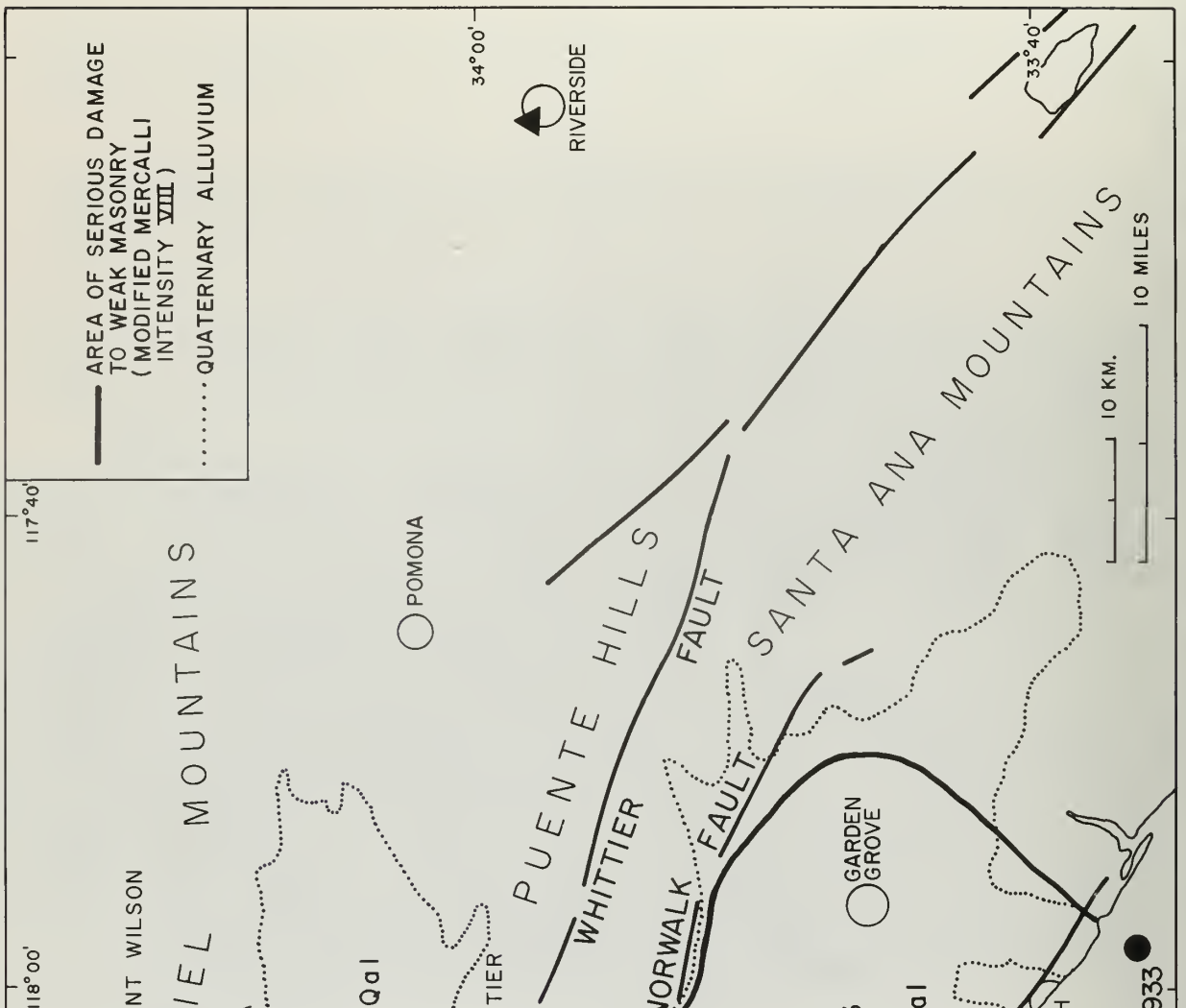


Figure 14. Map of a portion of southern California showing the area most strongly affected by the Long Beach earthquake, March 10, 1933. Isoseismal line corresponds approximately with limit of intensity level VIII of the Modified Mercalli scale of 1931. Selected epicenters (1933-1944) also plotted. (From Richter, 1958, p. 457, fig. 23-11)

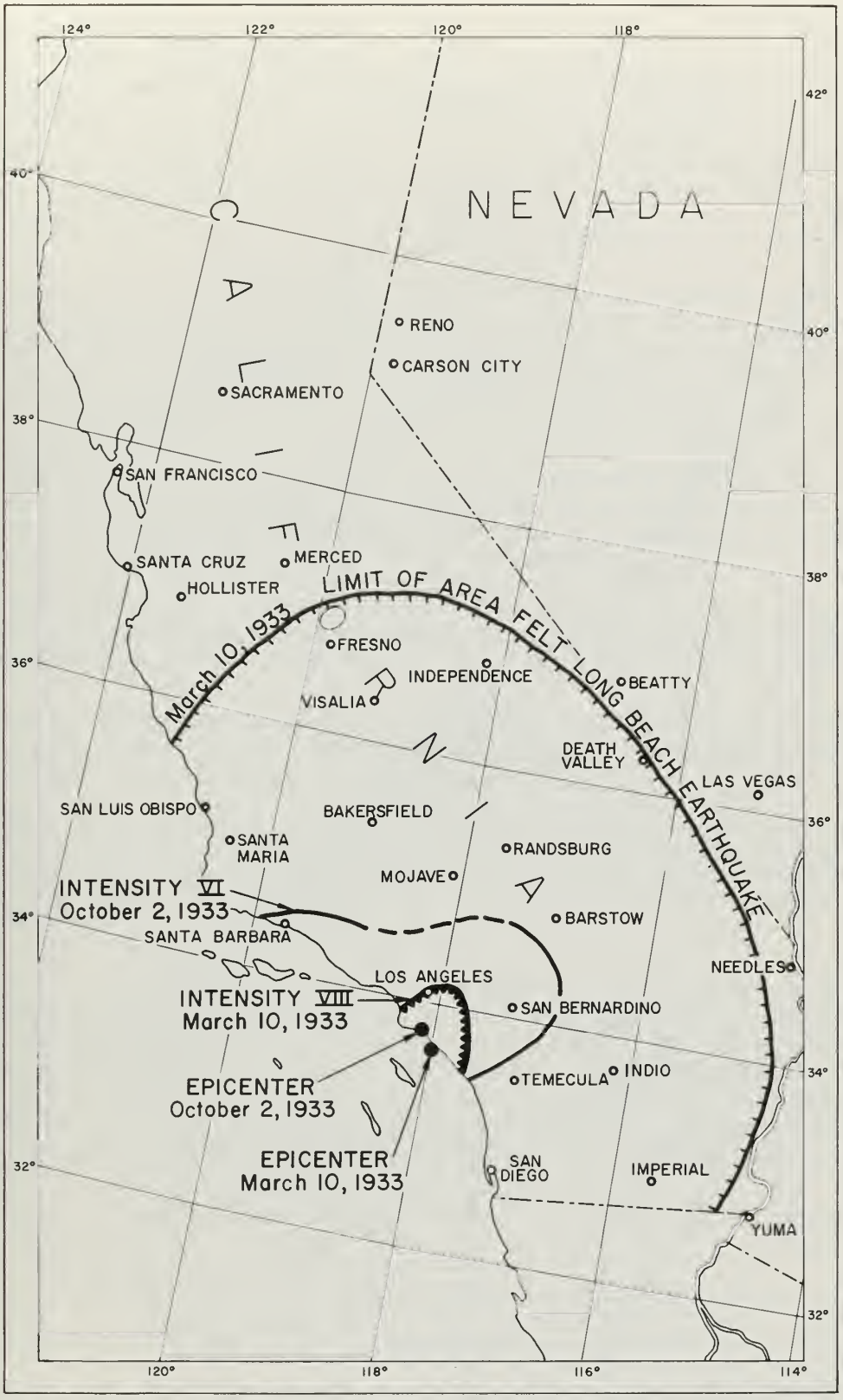


Figure 15. Area affected by March 10, 1933, Long Beach earthquake and October 2, 1933, Signal Hill earthquake. March 10 earthquake felt within area defined by hachured line; Modified Mercalli intensity VIII within line decorated with semi-circles. Modified Mercalli isoseismal (intensity VI) for October 2, 1933 earthquake also shown. (Source: United States Earthquakes, 1933, U. S. Coast and Geodetic Survey, fig. 2, p. 10).

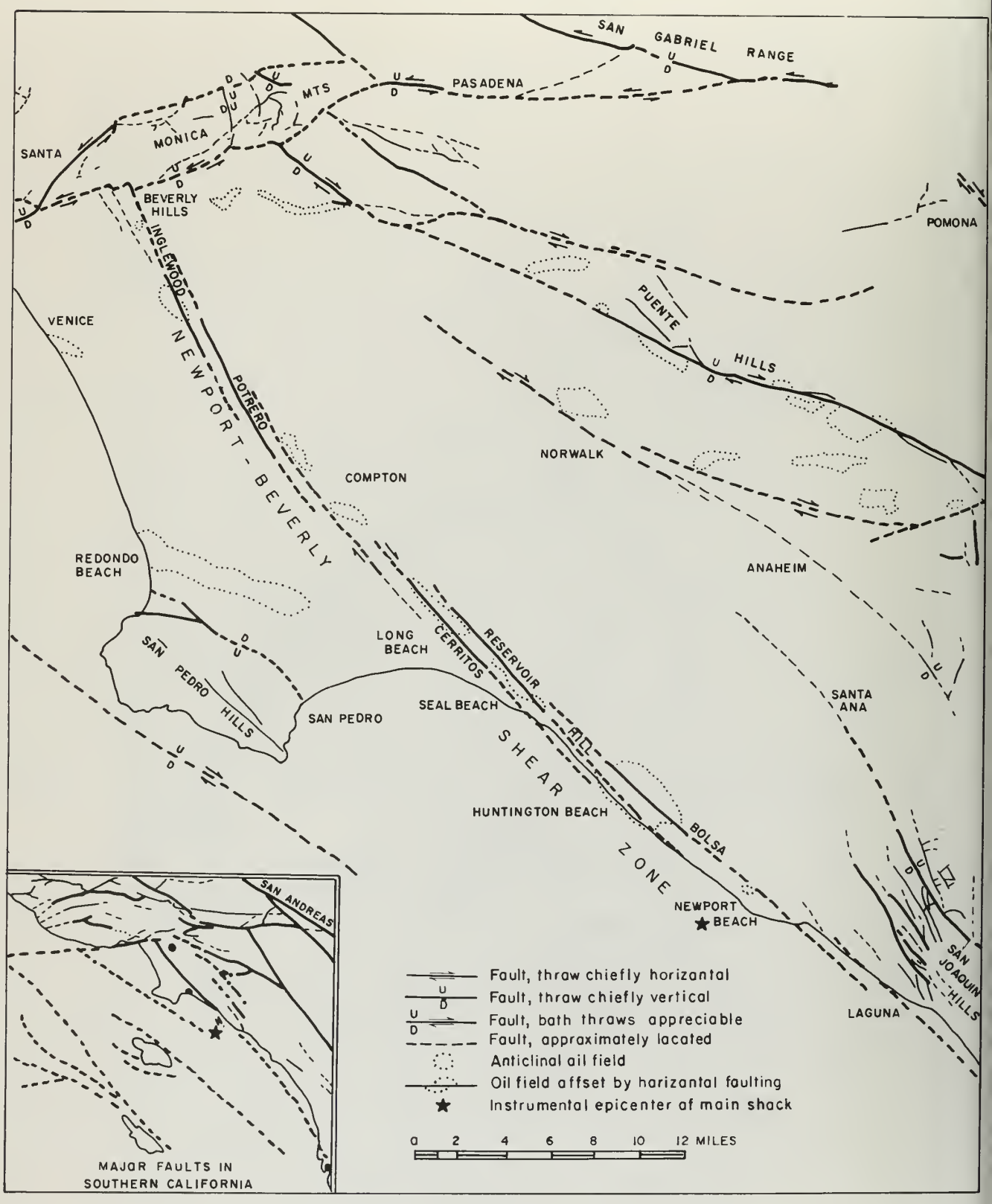


Figure 16. Fault map of the northern Los Angeles basin, redrawn from Eaton (1933, p. 733), which shows region most affected by the Long Beach earthquake. Eaton's caption reads: "Larger blank areas are alluvium or sea covered, and presumably contain unmapped faults. Notice junction of northwest-striking series with that of east-west transverse chain. Deep-seated horizontal faults -- long, comparatively straight fractures -- are seismically most important. The major of these from east to west (see thumb sketch) appear to be the San Andreas, San Jacinto, Elsinore, Puente Hills, Newport-Beverly, Point Vincente, Santa Catalina, and San Clemente shears."

seismic sea wave (Clements and Emery, 1947, p. 312). A portion of the tide-gauge record for March 10, 1933, at San Pedro is reproduced in Emery's book (1960, figure 112). Emery commented (1960, p. 125) that "the Long Beach earthquake failed to produce a tsunami or to materially disturb the seiche, although it shook the gauge." Bittinger (1933, p. 260), who was on board the U.S.S. Louisville about 3 miles southeast by south of Long Beach, described the shuddering of the ship due to the earthquake. He also quoted other Naval records from ships in the vicinity, which indicate that the earthquake was felt as a shock aboard all the ships.

Intensity. Refers primarily to the degree of shaking at a specific locality; its assessment includes the effects of ground motion on people, structures, and their contents and on the earth's surface. Many of these effects, usually compared with those listed under the 12 categories of the 1931 Modified Mercalli scale of intensity, were observed by numerous people following the Long Beach earthquake.

It is common practice to draw "isoseismals"--lines separating areas of different intensity--on maps of the area affected by an earthquake. The production of such a map is complicated by the variables which affect the intensity of an earthquake at a specific place. Barosh (1969, p. 7) listed most of the variables as follows:

> ...earthquake magnitude; epicentral distance; acceleration, period, duration, and amplitude of seismic waves; type of ground; geologic structure; slope of ground; ground water; type of construction; quality of workmanship; and the natural period of buildings and sites.

Almost all of the papers dealing with the intensity of the Long Beach earthquake stress two factors that were most responsible for the extent and amount of damage. These two factors were summed up by Wood (1933, p. 51):

> ...much of the spectacular structural damage was due (1) to bad natural ground or grading--made land, or deep water-soaked alluvium or sand; and (2) to bad or unsuitably designed construction--bad foundation structures, little or no provision against the stresses caused by earthquakes, bad or unsuitable materials, bad workmanship, or some combination of these factors.

There is no published map of the area affected by the Long Beach earthquake showing areas of different intensity levels of the Modified Mercalli scale. Several maps, however, do show a single area of "greatest seismic effects" or "extent of severe shaking or serious damage" (figures 14-17). Figure 15 from "United States Earthquakes, 1933", of the U.S. Coast and Geodetic Survey, indicates the extent of the area affected by the Long Beach earthquake. A list of intensities that were reported from scores of localities in southern California are also given in this publication.

A good summary of the distribution of intensities over the Los Angeles area was given by Richter (1959):

> The Long Beach quake, originating on the Inglewood fault, developed intensity VIII M.M. over most of the alluviated area of the L.A. Basin proper [figure 14]..There were a few isolated spots of intensity IX on the worst ground, for example at the coast adjacent to the mouth of the Santa Ana River. Intensity VII extended into the southern part of the Los Angeles business center; and further north there was much damage to weak masonry and in the interiors of many large business buildings, where intensity might be rated between VI and VII. The limit of VI, as represented by damaged chimneys, is drawn by Martel (1936) to include a much wider area. Intensities ranging from VI to VII, with corresponding damage, developed on the sand dunes toward the coast westward. On the principally Tertiary block of the San Pedro Hills intensity was barely VI, contrasting sharply with serious damage nearby in San Pedro and Long Beach.

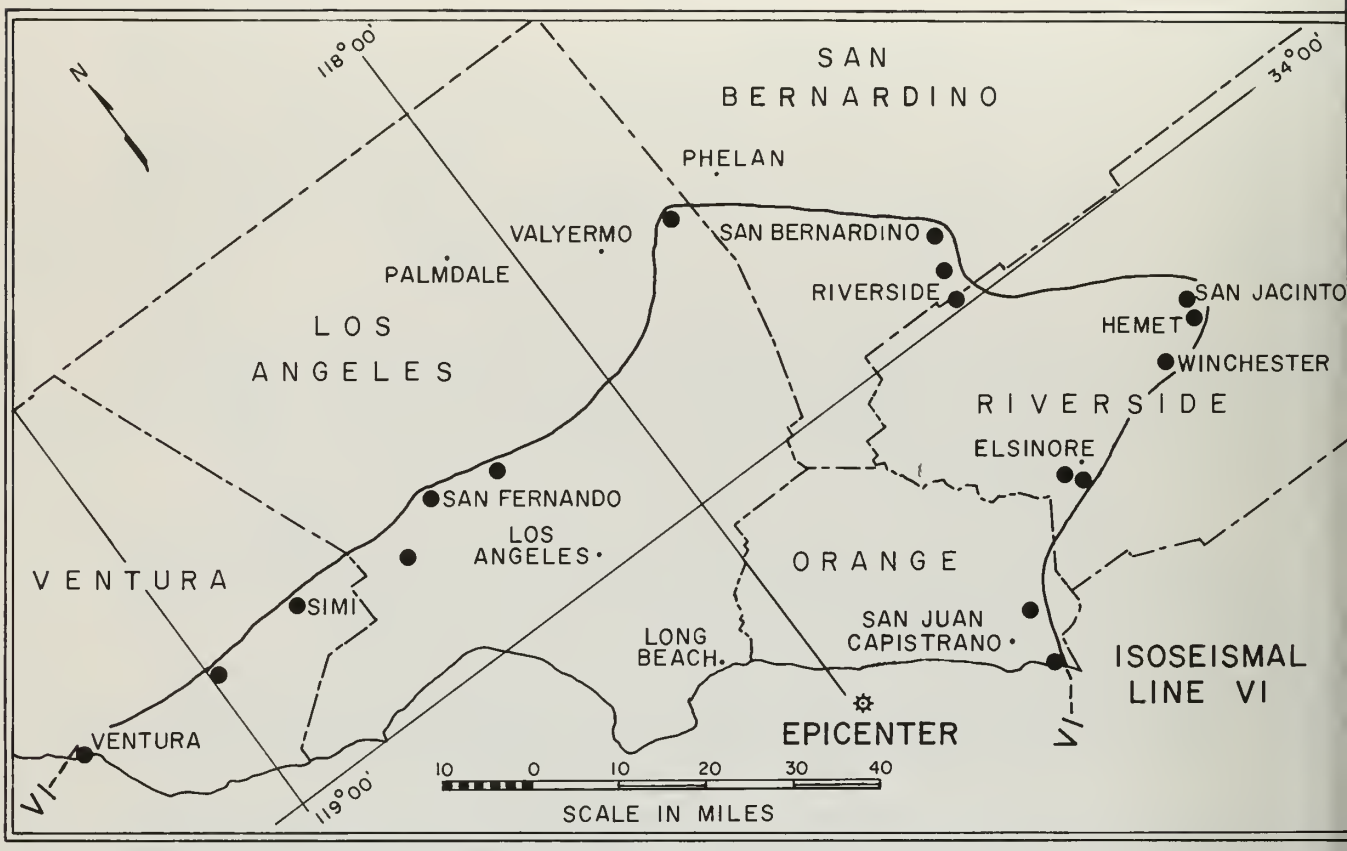
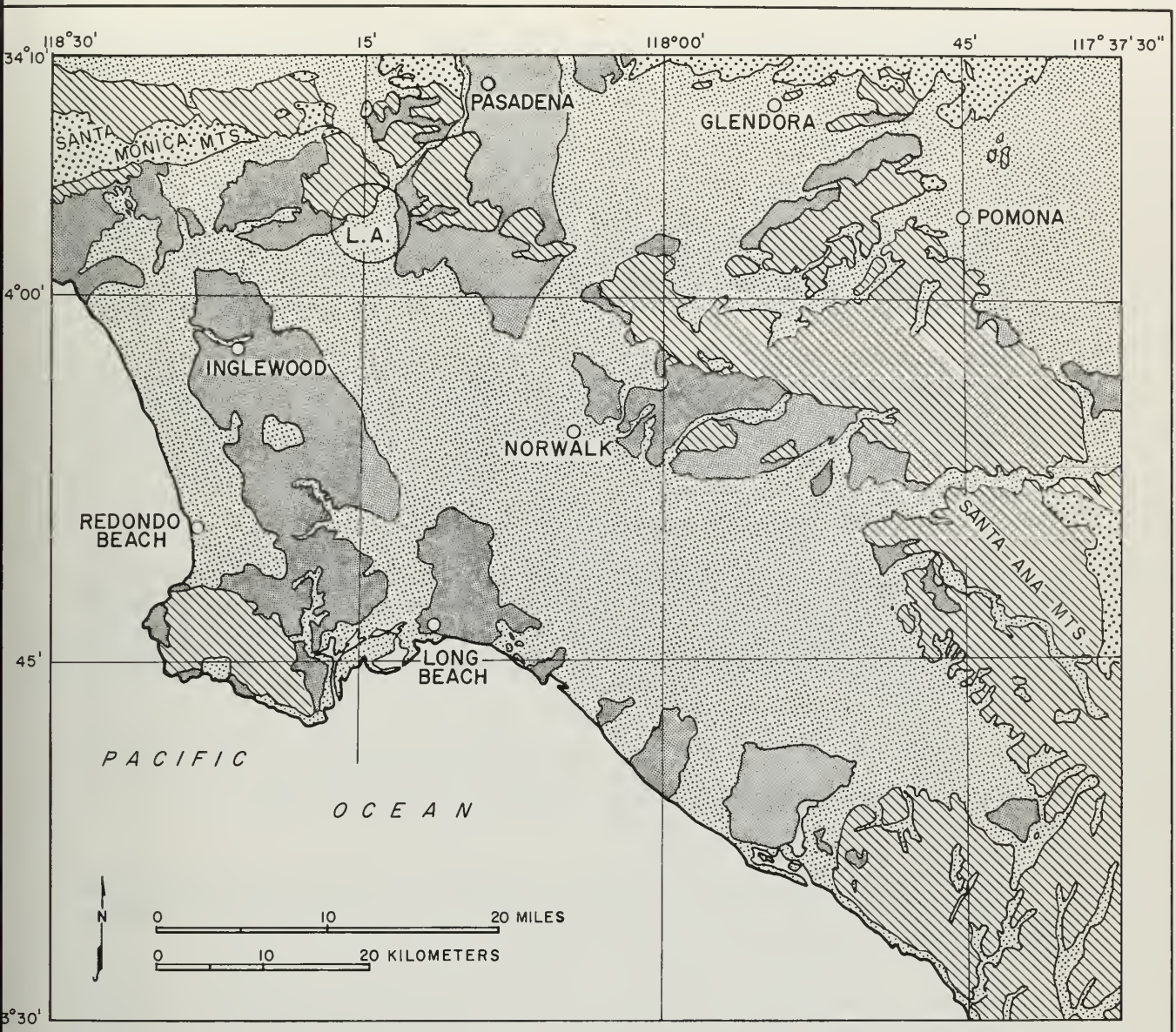


Figure 17. Isoseismal line for Modified Mercalli scale intensity VI for Long Beach earthquake added to map from Martel (1936, p. 145 fig. 110). Circles indicate damaged chimneys most remote from epicenter.

The map which was drawn by Martel (1936), referred to above, is given as figure 17. An "isoseismal" line has been added to Martel's map, at the limit of reported intensity VI effects. Martel (1936) also prepared a very detailed--block by block--map of Long Beach which shows the percentage of damage (based upon their assessed value) sustained by structures.

Inasmuch as the assessment of intensity levels is based upon observed damage and other earthquake related effects, it does not allow a precise determination of the natural effects of ground to be made because of the variability of construction quality, age, and intended use of structures. The value of intensity is demonstrated by microregionalization maps (Richter, 1959). This type of map (figure 18) is useful for suggesting the intensity that can be expected at a locality during a hypothetical large earthquake (an earthquake risk map). The importance of the type of ground is easily seen by comparing the microregionalization map (figure 18) with the preceding figures which show "isoseismal" lines. A major difference between isoseismal maps and the microregionalization diagram results from the non-directional nature of the hypothetical shock in the latter. For actual earthquakes, however, intensities are controlled by the distance from the epicenter, as well as by geological structural features and local ground conditions. Intensity maps show that effects of the Long Beach earthquake were essentially elliptical in plan, presumably a result not only of the distribution of the rocks and alluvium (figure 18) but also related to the trend of the major structural features.

The argument discussed earlier (page 67) that because the major damage, and hence the intensity, centered about a point near Signal Hill or Compton and, therefore, that the epicenter as determined by seismologists was incorrectly located offshore of



EXPLANATION

IX Quaternary alluvium, dune sand and landslide areas

VII Tertiary sedimentary rocks and volcanics

VIII Quaternary consolidated deposits

VI Granitic rocks and Mesozoic sedimentary and metamorphic rocks

gure 18. Microregionalization map of Los Angeles basin, southern California, showing probable maximum intensity (Modified Mer-lli scale) as depicted by Richter (1959, p. 129). Geology from Schoellhamer, Vedder, and Yerkes, California Division of Mines Bulletin, 0, Part II, Chapter 5, Plate I. (After Barosh, 1969, U. S. Geological Survey Bulletin, 1279, fig. 30, p. 46).

Newport is invalid for several reasons. (1) The effect of ground: the materials underfoot have more influence on the intensity than the nearness of the epicenter within the region affected by a shock. An excellent example of this fact comes from the lists in "United States Earthquakes, 1933" (U.S. Coast and Geodetic Survey). The intensity on alluvium at San Pedro was VII while that on rock at nearby Point Fermin lighthouse was reported as III or less. (2) As pointed out by Richter (1958, p. 142):

> There is evidence, which should be regarded less as established fact than as working hypothesis, that in the neighborhood of the epicenter the vertical component of motion is larger relative to the horizontal components than elsewhere. Near the epicenter this effect would decrease the ordinary manifestations of intensity...and cause an underestimate of the actual shaking.

(3) The intensity of the earthquake could not be assessed at the epicenter because it was at sea. (4) Within the first few hours after the principal shock, the aftershocks were almost evenly distributed throughout the length of the segment of the fault zone between Newport and Signal Hill. (5) Finally, as Benioff pointed out, knowing the location of the epicenter does not mean that the extent of faulting or the area from which the maximum destructive energy radiated are known.

The implications of the Long Beach earthquake experience, especially for planners and engineers, should be clear. Within the limits of the data available to seismologists the effects of earthquakes centered on the Newport-Inglewood structural zone can be predicted with reasonable confidence. Conclusions based on the foregoing summary are given on page 98.

Earthquake History, March 1933 to 1972

In the months immediately following the March 10, 1933, Long Beach earthquake, literally hundreds of aftershocks were felt in the Los Angeles-Long Beach-Newport area. The aftershock activity is discussed on page 70.

A review of "Seismological Notes" in the Bulletin of the Seismological Society of America for the years 1933 to 1940 reveals that at least 250 earthquakes were reported felt in the following localities (all of which could be affected by shocks originating along the Newport-Inglewood zone): Anaheim, Balboa, Bell, Beverly Hills, Compton, Costa Mesa, Culver City, Downey, Gardena, Hawthorne, Huntington Beach, Huntington Park, Hynes (Los Angeles County), Inglewood, Laguna Beach, Lennox (Los Angeles County), Lomita, Long Beach, Los Angeles, Maywood, Newport Beach, Norwalk, Pasadena, Redondo Beach, San Pedro, Santa Ana, Santa Monica, Seal Beach, Signal Hill, South Gate, Torrance, Venice, Vernon, Watts, West Los Angeles, Willowbrook (Los Angeles County), and Wilmington.

It is not uncommon for the earthquakes felt in some areas to be reported as "two shocks" within a few seconds of each other; therefore, some of these reports may refer to the two perceptible movements which are actually the result of a single seismic event (Richter, 1958, p. 27).

Table 9 lists the number of local earthquakes by year felt in the immediate vicinity of the Newport-Inglewood zone (but not necessarily originating thereon) for the interval between March 10, 1933, to December 31, 1939. The table shows that half of all the earthquakes felt in this area occurred in 1933 following both the Long Beach and Signal Hill earthquakes. Almost four-fifths of the earthquakes occurred before 1935.

Table 9. Number of reported earthquakes from March 10, 1933, to December 31, 1939.

1933	*1934*	*1935*	*1936*	*1937*	*1938*	*1939*
123	68	8	9	12	18	12

Most of the earthquakes listed in table 9 were felt in Long Beach and Huntington Beach. Relatively few were felt in Laguna Beach, Inglewood, Culver City, and other points at similar distances from the Long Beach-Seal Beach-Huntington Beach area. Almost all of the shocks were described as "slight" or "light" and were assigned intensities in the III to VI range of the Modified Mercalli scale of 1931.

The stronger local earthquakes occurring along the Newport-Inglewood zone and felt in the Los Angeles area since the Long Beach earthquake of March 1933 are listed in table 10. The December 27, 1939, shock was the strongest earthquake felt in the Long Beach-Compton-Watts areas since the 1933 shocks. It caused some damage in the Huntington Park-Long Beach area.

During the 1940s, several dozen earthquakes, which had epicenters along the Newport-Inglewood zone, were reported from localities along the zone. Most of these earthquakes were described as "slight" or "light" and were felt in one or two towns. The earthquakes of October 21, 1941, and June 18, 1944, have special significance because each one was associated with subsurface movement on faults in oil fields resulting in damage to oil wells. Both of these events are discussed in detail on pages 88 thru 91.

Table 10. Stronger local shocks along the Newport-Inglewood zone, March 1933 through 1972. (Source: Seismological Notes, Bull. Seismol. Soc. America).

Date	*Locality data*	*Intensity (Modified Mercalli)*	*Magnitude*	*Epicenter North latitude*	*Epicenter West longitude*	*Depth of focus*
1933 Oct. 2	Signal Hill (Long Beach, Los Angeles, Compton, Bell)	VI	5.4	33° 47′	118° 09′	
1939 Dec. 27	Long Beach (Huntington Park, and Long Beach damaged)	VI	4.5	33° 47′	118° 12′	
1941 Oct. 21	Gardena (damage in west Dominguez oil field)	VII	4.9	33° 49′	118° 13′	
1941 Oct. 22			3.8	33° 52′	118° 13′	
1944 June 18	Dominguez Hills 16:03:33 PST	VI	4.5	33° 52′	118° 13′	
1944 June 18	Dominguez Hills 19:06:07 PST	"sharp jarring"	4.4	33° 52′	118° 13′	
1949 Dec. 26	Inglewood and Westchester (El Segundo, Torrance, Hawthorne, Hollywood)	"sharp"	?	?	?	
1961 Oct. 4	Orange County		3.7	33.8°	117.8°	18 km
1961 Oct. 20	Orange County 4 larger shocks out of 8 tremors		3.9	33.7°	117.9°	19 km
1961 Oct. 20			4.6	33.6°	118.0°	17 km
1961 Oct. 20			4.2	33.7°	118.0°	20 km
1961 Oct. 20			4.2	33.7°	118.0°	27 km
1961 Nov. 20	Orange County (with 3 aftershocks)		4.0	33.7°	117.9°	17 km
1965 Nov. 12	Felt over 800 square miles of southwest Los Angeles County, most sharply in Santa Monica, Inglewood, Baldwin Hills		3.0	34.0°	118.3°	16 km
1966 Oct. 2	Felt over southwest Los Angeles County, felt sharply in Los Angeles		3.8	34.0°	118.3°	11 km
1967 May 12	Between South Gate and Lynwood, felt in Pasadena		2.9	33° 55.8′	118° 13.2′	10 km
1969 Oct. 27	Laguna Beach (offshore)		4.5	33° 32.7′	117° 48.4′	6 km
1970 Sept. 14	Felt in Inglewood, Culver City, and West Los Angeles area		3.0	34° 3.7′	118° 21.0′	8
1970 Sept. 23	At least 5 shocks felt in Culver City, Hawthorne, Hermosa Beach, Inglewood, Torrance, Santa Monica, Hollywood, Baldwin Hills, West Los Angeles, Manhattan Beach	V	4.2	34° 00′	118° 17′	10 km
1970 Sept. 23	Felt in Inglewood-Torrance area		3.3	33° 54′	118° 20′	10 km
1970 Sept. 23	Felt in Inglewood-Torrance area		3.2	33° 54′	118° 20′	10 km
1970 Sept. 23	Felt in Inglewood-Torrance area		3.2	33° 50′	118° 21′	10 km

A number of apparent earthquakes (Richter, 1958, p. 155-156) which occurred in the Terminal Island area of the Wilmington oil field between 1947 and 1961 are not listed in table 10. Faulting, which accompanied these tremors, caused several million dollars worth of damage to oil wells. The seismograms (Richter, 1958, p. 155) for these events differ from those of "normal" earthquakes by having" a relatively large development of long-period motion...and a lack of sharpness in the beginning of motion." Richter (1958, p. 155) has explained these events as "slumping on an enormous scale, incidental to subsidence," which he attributed to the "removal of support by oil operations" in this field. One such event occurred on April 6, 1933, during the aftershock activity of the Long Beach earthquake and, as Richter points out, before oil development in the harbor area began. It appears, therefore, that the April 1933 event was triggered by true tectonic activity causing "slumping" to occur in the Wilmington area.

EARTHQUAKE OF OCTOBER 21, 1941

The epicenter of this shock was located west of the Long Beach (Signal Hill) oil field and south of the Dominguez oil field (figure 19). Two shocks were reported on October 21, 1941, followed by a minor aftershock on October 22, 1941. The epicenter of the minor aftershock (taken from Gutenberg, 1943, p. 508) has been added to figure 19. It should be pointed out that the epicenter for this minor shock was misplotted in figure 28-14 of Richter (1958, p. 497) (see figure 14 this paper). The October 21, 1941, earthquake was the strongest shock to be felt along the zone since the October 2, 1933, event, which was centered about 3 miles away, east of Signal Hill.

As a result of this earthquake, subsurface displacement on a fault associated with one of the structures of the Newport-Inglewood zone was proven for the first time by damage to oil wells in the west Dominguez oil field.

According to Bravinder (1942), two groups of wells were affected. Breaks in the southerly group of weils ranged in depth from 5,600 feet to 6,784 feet, but the damage could not be correlated to movement along any known fault plane. In the northerly group, however, six wells were damaged at depths ranging from 5,320 to 6,130 feet. The damage points in each well correspond with the intersection of the well with a previously recognized south-dipping reverse fault that strikes approximately parallel to the axial trace of the Dominguez anticline.

The fault on which displacement took place is one of a series of such faults that "increase in number and amount of throw with depth, but die out as they are traced upward in the section" (Bravinder, 1942, p. 390). The disappearance of these faults toward the surface explains the lack of damage at shallower levels in the wells. Richter (1958, p. 156), who has called this occurrence and the 1944 case "triggered slumps," suggested that "the damaging displacements must have been triggered, either by the direct shaking of the earthquake or by the readjustment of the local strain pattern."

EARTHQUAKES OF JUNE 18, 1944

Two small earthquakes (magnitude 4.5 and 4.4) occurred in the Dominguez Hills and were followed by two smaller shocks (2.9 and 2.7 magnitude) on June 18, 1944. These events were followed on June 19, 1944, by three small shocks. The epicenters of the two larger shocks are shown in figure 19. Damage to 16 oil wells in the Rosecrans oil field, associated with the earthquakes, was attributed to movements along an east-west-trending, south-dipping reverse fault.

Martner (1948) presented an account of the earthquakes and damage. The similarities to the October 21, 1941, event discussed above are remarkable. With the exception of two wells, damaged at depths of 2,726 and 3,306 feet, the damaged portions were in the range 4,806 to 6,533 feet. These depths are similar to those for damage during the 1941 event.

Well damage was distributed along a south-dipping fault that "increases both in displacement and dip at depth and decreases toward the surface" (Martner, 1948, p. 110). The map (figure 19), which Martner prepared to indicate the relationship between the 1941 and 1944 occurrences, shows that the well damage of both shocks occurred not "along the fault on which the epicenters lie, but was due to a secondary movement along another fault" (Martner, 1948, p. 117). Martner (1948, p. 118) concluded:

> A study of the compressions and dilations of first motion at the various stations...is in perfect agreement with the general movement of the region, namely, a differential movement in a northwest direction on the west side and southeast on the east side of the main Inglewood fault zone, as Gutenberg has shown by a study of many southern California earthquakes (Gutenberg, 1941).

There is no published record available on damage to oil wells in other fields of the Newport-Inglewood zone. In the cases of the 1941 and 1944 local earthquakes, discussed above, the relation between earthquakes and simultaneous displacement of subsurface faults resulting in the damage to numerous wells is easily demonstrated. Damage to oil wells in the Inglewood field occurred during distant earthquakes on two separate occasions (California Department of Water Resources, 1964, Investigation of failure--Baldwin Hills reservoir, p. 42). Two oil wells were damaged in the Vickers zone on February 18, 1963; and another oil well was damaged at a depth of 1,520 feet on March 10, 1963. Hudson and Scott (1965, p. 178) pointed out that the earthquakes involved had magnitudes of 3.4 and 3.0, respectively. It is possible that earthquakes of such low magnitudes can cause near-surface displacements partly because of the contributing factor of local subsidence, which in the Inglewood oil field totaled nearly 6 feet during the period 1924-1963 (Castle and Yerkes, 1969, p. 30).

During the past 25 years, the number of earthquakes felt in the vicinity of the Newport-Inglewood zone has been much less than during the 25-year period before 1945. A check of "Seismological Notes" in the Bulletin of the Seismological Society of America indicates that an average of between two and three local earthquakes were felt at various localities along the zone since 1945. The most active year was 1961 (see table 10), when six earthquakes with magnitudes greater than 3.7 occurred. The epicenters of these earthquakes lie very near to the epicenter of the Long Beach earthquake. However, whereas the focal depth of the 1933 shock was estimated to be 10 km (Wood, 1933), the focal depths for the 1961 shocks ranged from 17 to 27 km (table 10). The farthest south earthquake along the Newport-Inglewood zone to be instrumentally recorded occurred on October 27, 1969, offshore from Laguna Beach.

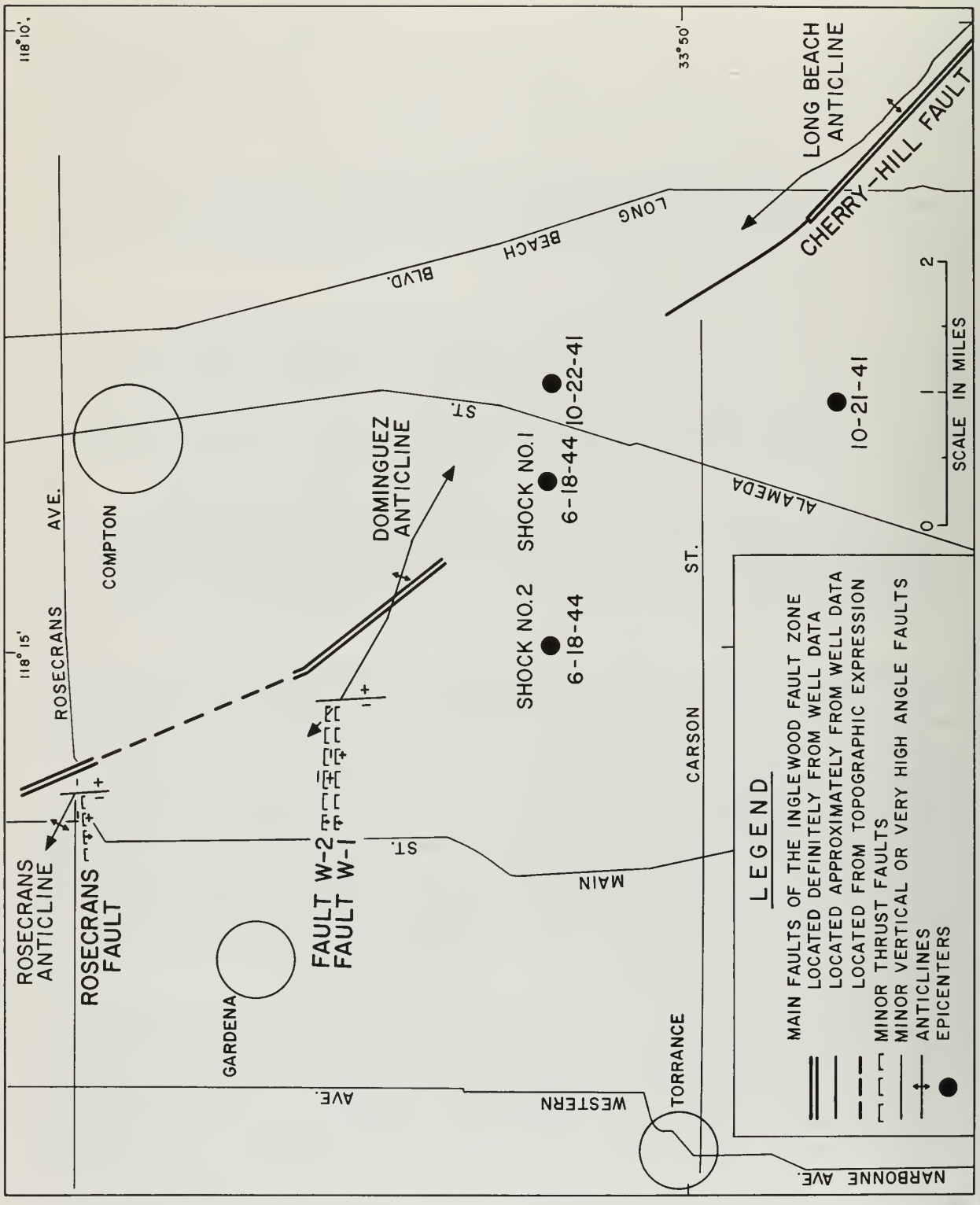


Figure 19. Map of the Rosecrans-Dominguez-Signal Hill area, Los Angeles County, California, showing the relation of subsurface thrust faulting to the geologic structure of the oil fields and the epicenters of the June 18, 1944 and October 21 and 22, 1941 earthquakes. (After Mather, 1948, Seism

Implications of this event with respect to an extension of the Newport-Inglewood structural zone are discussed on page 57. The 1933, 1961, and 1969 shocks all occurred along a segment of the Newport-Inglewood zone that lies offshore from Newport Beach. An inferred location of this fault trace on the basement surface is shown by Yerkes *et al.* (1965, p. A4). Coincidently, Yerkes *et al.* (1965, p. A34) mention also that in the San Joaquin Hills "numerous long thin [Miocene] dikes of phaneritic hypersthene andesite, which are emplaced along faults, radiate northward from a point near the offshore extension of the Newport-Inglewood zone."

CONCLUSIONS

The Newport-Inglewood structural zone is seismically active. Earthquakes strong enough to be felt along the zone are, not only numerous, but frequent. A review of felt earthquakes is perhaps a better index of the "hazard potential" of activity than the often compiled map of epicenters for all instrumentally recorded tremors because "felt" earthquakes are those capable of causing damage. Although the historical record is brief, it does indicate that potentially damaging shocks have occurred several times each decade (except for the 1950s--see table 10). There is no reason to believe that this pattern will change in the near future.

The effects of the larger earthquakes, particularly the 1933 Long Beach earthquake, are well documented and provide an excellent guide of what to expect from similar events in this part of the Los Angeles basin. The historical record indicates that surface displacements on known faults along the zone have not occurred. However, subsurface movement on pre-existing faults in three of the oil fields along the zone has been associated with earthquake activity.

It is generally conceded that the type of ground exerts a controlling influence on the intensity of shaking at any given locality during a local earthquake. Abundant examples of this are found in the records of historical earthquakes. Although preliminary estimates of the horizontal acceleration attained during the first few seconds of the Long Beach shock ranged between 0.3 g and 1.0 g (Heck, 1933) refinement of these estimates indicates that values up to 0.23 g for the horizontal acceleration are more likely (Heck and Heumann, 1933, p. 805). It is thus important to design structures to make them capable of withstanding high, especially horizontal, accelerations. Shaking of structures, however, may not represent the greatest hazard during future earthquakes, if building codes are realistic and enforced. Shaking of the ground and attendant disruption due to lurching remains a serious problem.

Disruption of the ground surface, not necessarily along known faults, will probably occur during any future local shock of the magnitude and duration of the Long Beach earthquake. The extensive cracking of the ground in the vicinity of the mouth of the Santa Ana River, in Sunset Gap, near Seal Beach, and around Compton as the result of inelastic response of unconsolidated materials to shaking may actually represent a major cause of damage during future shocks. Unless they are specifically designed to withstand ground-surface disruption--a solution which is considered economically infeasible--single-family residences built on "bottomland" may sustain damage representing a significant proportion of their total value.

A necessary conclusion from study of the earthquake history is that damage is not restricted to a narrow zone coincident with the surface expression of the Newport-Inglewood structural zone. Artificially filled land is now much more widespread than in 1933. The possibility for large areas within the vicinity of the zone to react to strong shaking by "lurching" or disruption of the surface in an unpredictable manner makes it imperative to consider these areas carefully. For, although it is possible to predict that during the next moderately damaging earthquake non-fault surface breaks will form, it is not possible to delineate the location of the expected ruptures.

Judging from the historical record, especially with respect to those earthquakes which originated beneath the ocean floor such as the Long Beach event, tsunamis are not to be expected from earthquakes along the Newport-Inglewood zone--at least for shocks below 6.5 magnitude. However, because numerous other nearby sub-ocean

faults are also active and because a seismic sea wave was associated with more than one historical shock (July 10, 1855, and August 10, 1879), those concerned with siting of structures on the nearshore, low-elevation areas in the vicinity of the Newport-Inglewood zone should consider the possibility of damage from this cause.

One additional geologic effect of earthquakes is the probable relation between elevation changes and earthquakes. While it is clear that subsidence, centering over and extending beyond oil fields, can accompany the withdrawal of pore fluids as well as tectonic processes, it is likely that any absolute uplift along the Newport-Inglewood zone is an effect of continuing tectonism. The area east of Signal Hill, whose uplift was recorded by leveling surveys run before and after the Long Beach earthquake, probably rose as a result of the Long Beach earthquake (figure 12; Gilluly and Grant, 1949). A less well-bracketed case of uplift along Manchester Boulevard in Inglewood (Grant and Sheppard, 1939) may have been related to the 1920 Inglewood earthquake. The possibility for elevation changes resulting from future earthquakes should be considered by those who design facilities whose operation may be affected by such changes.

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APPENDIX A

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------Earthquake resistance of plaster on walls: August 30, 1935, p. 18.
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APPENDIX B

ANNOTATED BIBLIOGRAPHY OF SEISMOLOGICAL AND GEOLOGICAL REFERENCES TO THE LONG BEACH EARTHQUAKE

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Using the data from the distribution of aftershocks and applying the concepts of the elastic rebound theory, Benioff determined that faulting extended from the focus to Signal Hill (27 km) at a faulting speed of approximately 4.2 km/sec. Also discussed Clements' (1933) paper, pointing out that transverse, rather than longitudinal, waves cause most of the damage.

Benioff, Hugo, 1951, Earthquakes and rock creep (Part I: Creep characteristics of rocks and the origin of aftershocks): Bulletin of the Seismological Society of America, v. 41, p. 31-62.

Discusses aftershock sequence of the Long Beach earthquake attributing it to elastic afterworking of the fault rock. Also points out that the Signal Hill (October 2, 1933) earthquake was not an aftershock of the Long Beach quake but was an independent event accompanied by its own sequence of aftershocks.

Buwalda, J. P., 1933, What happened geologically: Unpublished paper presented at the American Society of Mechanical Engineers Meeting, Los Angeles, California, April 12, 1933. Abstract published in Science, v. 78, p. 148-149.

California Department of Water Resources, 1968, Sea-water intrusion: Bolsa-Sunset area, Orange County: California Department of Water Resources Bulletin 63-2, 167 p.

Refers to the surface effects of the Long Beach earthquake in the Santa Ana Gap and Sunset Gap areas of Orange County.

Clements, Thomas, 1933, Notes on the fall of columns during the Long Beach earthquake: Science, v. 78, p. 100-101.

Noting the apparent convergence of lines indicating the direction of fall of tombstones in the vicinity of Compton, Clements inferred that the epicenter of the Long Beach earthquake was located there and not offshore at Newport. See Benioff (1938) for different interpretation of Clements' data.

Clements, Thomas, 1936, Experiments on the fall of columns: Bulletin of the Seismological Society of America, v. 26, p. 229-234.

An attempt to resolve the conflict of opinion regarding the interpretation of the significance of the fall of gravestones during the Long Beach earthquake. This paper was also commented upon by Benioff (1938).

Clements, Thomas, and Emery, K. O., 1947, Seismic activity and topography of the sea floor off southern California: Bulletin of the Seismological Society of America, v. 37, p. 307-313.

Refers to the fact that the U. S. Coast and Geodetic Survey tide curves do not show any tsunamis but do show the actual earthquake.

Dahm, C. G., 1936, Velocities of P and S waves calculated from observed travel times of the Long Beach earthquake: Bulletin of the Seismological Society of America, v. 26, p. 159-171.

Eaton, J. E., 1933, Long Beach, California, earthquake of March 10, 1933: Bulletin of the American Association of Petroleum Geologists, v. 17, p. 732-738.
Mostly a discussion of the regional tectonics of the Newport-Inglewood zone. Notes that the very small amount of damage to oil wells along the zone indicates the near-surface faults did not move sympathetically with the deep-seated shear.

Gilluly, James, and Grant, U. S., 1949, Subsidence in the Long Beach harbor area, California: Bulletin of the Geological Society of America, v. 60, p. 461-529.
Present map of the Long Beach region on which are plotted the elevation changes detected by comparison of leveling surveys run before and after the Long Beach earthquake. The changes include an area of maximum uplift of 0.610 foot northeast of Signal Hill.

Gutenberg, Beno, 1941, Mechanism of faulting in southern California indicated by seismograms: Bulletin of the Seismological Society of America, v. 31, p. 263-302.
Discusses the patterns of compressions and dilations produced by direct longitudinal waves during many local California earthquakes including the Long Beach and Signal Hill shocks.

Gutenberg, Beno, 1943, Earthquakes and structure in southern California: Bulletin of the Geological Society of America, v. 54, p. 499-526.
Discusses the relations between depth of foci and crustal structure. Includes a map of the Long Beach region on which are plotted the epicenters and directions of compressions and dilations for seven shocks felt in the area before 1942.

Heck, N. H., 1933, Strong-motion records of Long Beach earthquake: Engineering News-Record, v. 110, no. 14, (April 6, 1933), p. 442-443.
Reproduces the seismograms recorded at three local accelerographs during the Long Beach earthquake and points out that unusual accelerations of 0.3 to 1.0 g occurred during the first few seconds of the earthquake.

Heck, N. H., and Neumann, Frank, 1933, Destructive earthquake motions measured for the first time: Engineering News-Record, v. 110, no. 25, (June 22, 1933), p. 804-807.
Points out that the strong-motion accelerograph records at three southern California stations were the first time that earthquake motion has been measured within 20 miles of the epicenter of a destructive earthquake and includes an analysis of the records.

Hillis, Donuil, 1933, Cracks produced by Long Beach, California, earthquake: American Association of Petroleum Geologists Bulletin, v. 17, p. 739-740.
Describes and illustrates a 6-foot long, 5-foot deep crack which trended north 45° west on the eastern outskirts of Compton. Infers that the crack formed as a result of the inelastic response of unconsolidated deposits to the passing of earthquake shock waves.

La Rocque, G. A., Jr., 1941, Fluctuation of water level in wells in the Los Angeles basin, California, during five strong earthquakes 1933-1940: American Geophysical Union Transactions, p. 374-386.
Discusses the earthquake-related surges in water levels and the changes in water levels following earthquakes. Points out that there was a semi-permanent rise in water level in 24 out of 25 wells monitored following the Long Beach earthquake and that the greatest change in level occurred northeast of Signal Hill.

Maher, T. J., 1933, Abstract of reports received regarding the earthquake which occurred in southern California on March 10, 1933: U. S. Coast and Geodetic Survey, Field Station, San Francisco, California, 64 p. (Report described in Bulletin of the Seismological Society of America, v. 23, p. 131.)
Contains information from hundreds of reports from southern California localities, many of which describe surface effects of the major earthquake and aftershocks as well as the predominant observations on damage to structures.

Martel, R. R., 1936, A report on earthquake damage to Type III buildings in Long Beach *in* U. S. Coast and Geodetic Survey Special Publication 201, p. 143-162.

Attempted to determine the variation in intensity of the earthquake within Long Beach and the relation between building type and location to the amount of damage. Presents a map of Long Beach on which is plotted the block-by-block percentage of damage to buildings. Also includes a map of southern California on which the limits to damage of chimneys (outer boundary of intensity VI) is shown.

Millikan, R. A., chairman, 1933, Earthquake hazard and earthquake protection: Joint Technical Committee on Earthquake Protection, June, 1933, Los Angeles, California, 13 p.

Report published in cooperation with the Los Angeles Chamber of Commerce and prepared by a group of seismologists, geologists, engineers, contractors, and architects which briefly summarizes the regional structure, earthquake history, risks, and protection from earthquakes and the effects of the Long Beach earthquake. Also includes recommendations on design of structures and preparations for other seismic events.

Neumann, Frank, 1935, United States earthquakes, 1933: U. S. Department of Commerce, U. S. Coast and Geodetic Survey, Washington, D. C., Serial No. 579, p. 9-35.

Contains a brief summary of the earthquakes and includes a list of reports subdivided according to intensity. An isoseismal map of the entire region affected by the earthquake can easily be prepared from this list. The reports are essentially the same as those abstracts by Maher (1933). Also quotes Wood's (1933) summary article and presents a discussion of the three accelerograph records which were also discussed by Heck (1933) and Heck and Neumann (1933).

Nishkian, L. H., 1933, High seismic factors in recent earthquake: Engineering News-Record, v. 110, no. 15, p. 476.

By calculating the force required to cause the observed damage to some cross-bracing members in several different structures Nishkian concluded that seismic factors (horizontal accelerations) of 0.20 to 0.25 g must have been present.

Richter, C. F., 1935, An instrumental earthquake magnitude scale: Bulletin of the Seismological Society of America, v. 25, p. 1-32.

Contains the first calculation of the magnitude of the Long Beach earthquake (6.2). Also estimates the mean radii of the area of perceptibility (300 km), isoseismal IV (250 km), and isoseismal VII (25 km). Points out that the amount of energy of all the aftershocks was not a large fraction of that of the main shock and that, therefore, the small shocks do not release much of the accumulated strain. In other words, small shocks may not be "safety valves", but "symptoms", of accumulation of strain.

Richter, C. F., 1958, Elementary seismology: W. H. Freeman and Co., San Francisco, 768 p.

Briefly summarizes the Long Beach earthquake and includes a map of the Los Angeles region which depicts the "area of serious damage to weak masonry" (p. 497-499). Discusses foreshocks (p. 67), aftershocks (p. 69), the reason for the common report of "two shocks" (p. 27) (e.g., Clements, 1933), and Clements' (1933) application of Mallet's procedure for the determination of the direction of an epicenter by measuring the direction of fall of tombstones.

Richter, C. F., 1959, Seismic regionalization: Bulletin of the Seismological Society of America, v. 49, p. 123-162.

Discusses the distribution of intensities during the Long Beach earthquake and the relation between damage and ground conditions. Points out that intensity of shaking varies primarily with the nature of the ground and secondarily with the location of the active faults. Presents a microregionalization map of the Los Angeles basin of which geology is related to the maximum probable intensity that might be felt during local earthquakes.

Taber, Stephen, 1933, The location of earthquake epicenters: Science, v. 78, p. 283.

Discusses the lack of a seismic sea wave following the Long Beach earthquake and comments that, although an epicenter can usually be located by study of the distribution of damage, the nature of the ground must also be considered.

Wood, H. O., 1933a, Preliminary report on the Long Beach earthquake: Bulletin of the Seismological Society of America, v. 23, p. 43-56.

Primary basic reference on the various aspects of the Long Beach earthquake. Includes 22 excellent photographs of surface effects and damage resulting from the shock.

Wood, H. O., 1933b, Note on the Long Beach earthquake: Science, v. 78, p. 281-282.

Brief note abstracted from Wood's 1933a report.

Wood, H. O., 1947, Earthquakes in southern California with geologic relations: Bulletin of the Seismological Society of America, v. 37, p. 107-157 (Part I), p. 217-258 (Part II).

An attempt to correlate earthquake epicenters with known faults in California and a discussion of the typical depths of earthquakes in southern California. (Superseded by Allen *et al.*, Bulletin of the Seismological Society of America, 1965, v. 55, p. 753-797).

Wood, H. O., and Heck, N. H., 1961, Earthquake history of the United States, Part II-Stronger earthquakes of California and western Nevada: U. S. Department of Commerce, U. S. Coast and Geodetic Survey, Washington, D. C. (revised 1960 edition).

Very brief summary of the effects of the Long Beach earthquake (p. 38-39).

CALIFORNIA DIVISION OF MINES AND GEOLOGY
JAMES E. SLOSSON, STATE GEOLOGIST

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF CONSERVATION

PREPARED IN COOPERATION WITH THE LOS ANGELES COUNTY ENGINEER
AND THE LOS ANGELES COUNTY FLOOD CONTROL DISTRICT

NEWPORT INGLEWOOD
SPECIAL REPORT 114, PLATE 1

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Alamitos Heights

Landing Hill

Balsa Chico Mesa

Huntington Beach Mesa

Newport Mesa

Point Fermin

June 1920

June 1944

Oct. 1941

Oct. 1933

Inglewood fault

Parras fault

Avalon-Compton fault

Cherry Hill fault

Pickler fault

Northeast flank fault

Reservoir Hill fault

Seal Beach fault

High School of the Seal Beach - Inglewood fault

North Branch Inglewood fault

Los Angeles

Beverly Hills

Pasadena

Glendale

Burbank

Hollywood

Santa Monica

Venice

Inglewood

Huntington Park

Bell

Bell Gardens

Montebello

Commerce

Whittier

La Habra

La Puente

Pomona

Ontario

Chino

Mira Loma

Pedley

Cucamonga

Upland

Claremont

Monrovia

Arcadia

Temple City

San Gabriel

Baldwin Park

Covina

West Covina

El Monte

Monterey Park

Alhambra

Glendora

Azusa

San Dimas

La Verne

Duarte

Sierra Madre

Altadena

La Canada

Montrose

Glendale

Van Nuys

Reseda

Canoga Park

Woodland Hills

Encino

Sepulveda Dam

Whittier Narrows Dam

Santa Ana

Orange

Anaheim

Fullerton

Buena Park

La Mirada

Norwalk

Lakewood

Long Beach

Torrance

Redondo Beach

Hermosa Beach

Manhattan Beach

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Santa Fe Springs

Whittier

Irvine

Tustin

Costa Mesa

Newport Beach

Huntington Beach

Corona

Norco

El Toro

Laguna Hills

Trabuco Canyon

Escarpment

Point Vicente

Redondo Canyon

Pelican Hills

Mountain View

Sunset Beach

Seal Beach

Garden Grove

Westminster

Tustin

Irvine

Foothill Ranges

Coast Ranges

Valley

Plain

Mesa

Heights

Park

Hills

Canyon

Point

Dam

Reservoir

Estates

Beach

Harbor

Bay

Monica Bay

Pedro

Vicente

Fermin

Redondo

Palos Verdes

Inglewood

Baldwin

Rosecrans

Dominguez

Signal

Alamitos

Landing

Balsa Chico

Huntington Beach

Newport Mesa

Cheviot

Pacific Palisades

Santa Monica

Venice

Inglewood

Huntington Park

Bell

Bell Gardens

Montebello

Commerce

Whittier

La Habra

La Puente

Pomona

Ontario

Chino

Mira Loma

Pedley

Cucamonga

Upland

Claremont

Monrovia

Arcadia

Temple City

San Gabriel

Baldwin Park

Covina

West Covina

El Monte

Monterey Park

Alhambra

Glendora

Azusa

San Dimas

La Verne

Duarte

Sierra Madre

Altadena

La Canada

Montrose

Glendale

Burbank

Hollywood

EXPLANATION

FAULT

Dashed where approximately located; dotted where concealed

NEAR-SURFACE FAULT

Shown only along Newport-Inglewood zone. Delineated by ground-water studies; may be ground-water barrier other than fault (e.g., facies change). Queried where inferred solely on basis of topography.

ZONE OF DEFORMATION

Includes both topographic expression of folds and faults and the inferred deep-seated fault zone along which earthquakes take place. Width varies with complexity of surface expression.

MAJOR FOLD AXES

Anticlinal Axis showing direction of plunge

Synclinal Axis showing direction of plunge

(From U. S. Geological Survey Prof. Paper 420-A, 1965, fig.2)

UPLIFTS

Topographic expression of the structural zone

EPICENTERS

Selected damaging earthquakes associated with the zone

MAP OF THE NEWPORT-INGLEWOOD STRUCTURAL ZONE AND OTHER STRUCTURAL FEATURES OF THE LOS ANGELES AREA, SOUTHERN CALIFORNIA

1974

Scale 1:125,000

2 1 0 2 4 6 8 10 Statute Miles

5 4 3 2 1 0 5 10 15 Kilometers

Contour Interval 500 feet

Subsea Contour Interval 100 fathoms

Topographic base map enlarged from U.S. Geological Survey 1:500,000 scale map of California, 1969 edition

COMPILED FROM: Geologic Map of California, California Division of Mines and Geology, Long Beach (1962), Los Angeles (1969), and Santa Ana (1965) sheets; U.S. Geological Survey Professional Paper 420-A, 1965, fig.2; Preliminary geologic environmental map of the greater Los Angeles area, California, 1969, by C.M. Wentworth, J.I. Zionу, and J.M. Buchanan, U.S. Geological Survey, Reactor Technology (TID-25363); as well as sources used in above compilations.

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